Petrol Engine Development Strategy

Executive Summary

Submitted Towards the Award of Doctor of Engineering

A.J.Robinson MSc

March 2000

Petrol Engine Development Strategy

Synopsis

The automotive industry is becoming more global and cosmopolitan, while the markets are becoming fragmented and differentiated because of the sophistication of the customer. This requires the automotive manufacturers to have a product well suited to these factors more quickly and cheaply, which necessitates the accurate definition of the product. Two European automotive manufacturers NPI processes were studied and this showed that poor performance in the product definition phase was deemed to be a major reason for sub-optimal performance in both companies, even though the approaches were very different. It was therefore decided to develop and apply tools to assist in the development of petrol engines to overcome these deficiencies.

When these shortcomings are considered in the context of petrol engine development it can be seen through examination of the literature and industry that:

- There is no method for the translation of the values of the company or product into tangible engineering terms and in the context of this project, with focus on vehicle and engine performance. This can result in the poor positioning of a vehicle in the market due to inappropriate characteristics
- Having defined the required vehicle performance, it is not possible to demonstrate the feel of the vehicle until the hardware is physically available. This means that often there is a long lead-time between the setting of a target and the concept ratification through driving the new vehicle. This often results in a point of no (or very costly) return very early during the programme.
- Fuel economy is becoming an increasingly significant issue with the introduction of fiscal penalties for poor fuel consumption vehicles. There are currently no processes available for the calculation of steady state or drive cycle fuel economy which allow for the accurate modelling to include combustion, pumping and friction losses, and the control of the engine with the engine management system

To overcome these limitations three main groups of innovative tools/techniques have been developed and applied on new engine and vehicle programmes.

- Marque engineering: a proposal to translate the brand objectives into engineering terms has been developed to a level where the engine torque output can be linked to the product position
- Engine and vehicle performance simulation: a vehicle has been built to demonstrate how a new vehicle/engine will feel to drive by controlling the original engine performance to allow the simulation of the concept engine performance in the concept vehicle. This means it is possible to demonstrate and ratify a given engine/vehicle performance based on experience of the simulated product and to conduct sensitivity studies to discreet aspects of the performance feel of the vehicle
- Steady state and drive cycle fuel economy: simulation programs have been written that take the basic engine efficiency relationships and through manipulation it is possible to determine the exact operating point of the engine, steady state or transient, and then determine the fuel economy. In order to determine the exact operating point it is necessary to consider detailed component data and key calibration data. Therefore it is possible to understand the effects of small changes to engine geometry, components or calibration on the fuel used.

These developed techniques have been compared with traditional methods to determine the benefits in the concept confirmation phase of a new programme. This investigation showed that the reductions in phase duration, resource requirements and cost could be achieved in the order of 49, 27 and 17% respectively. This is coupled with the ability to obtain a more accurate product positioning through the capacity precisely to predict the product attributes.

To conclude, the ability to define the product well is paramount to the success of an automotive manufacturer, and in support of this my project has developed tools and techniques that will greatly assist the development of petrol engines.

Acknowledgements

The author would like to acknowledge the assistance from Mr. George Houghton and Mr. John Houldcroft of Rover Group, and Dr. Ali Veshagh and Dr. Kevin Neailey of the University of Warwick for their support and guidance throughout this project, along with a multitude of others from Rover and BMW who provided assistance, information, guidance and advice.

I also wish to acknowledge the support, help and encouragement from my wife Tara, and the welcome distraction provided by my children James and Matthew.

Declaration

The contents of this document have not been presented for a previous degree except where referenced and is the work of the author.

Table of Contents

1 Introduction

The automotive market has become more global and cosmopolitan. However, this global market has become more fragmented and differentiated because of the sophistication of the consumer. The result is that manufacturers are now competing on a product basis rather than within the traditional geographical boundaries, which compounds this fragmentation and globalisation. Thus the ability to have a product well suited to these complex factors with shorter programme times and lower programme costs is paramount to a company's success.

This need to shorten lead times, reduce programme costs and create a more differentiated product, is made at the same time as the engine is becoming increasingly complex to meet the needs of the customer and the legislator. The ability to conduct numerous design/build iterations is removed, as the shear task of integrating the entire system is so intricate. Tools and techniques that can be applied to assess large numbers of concepts without the need to produce physical parts would give major benefits to the new product introduction process.

Currently no tools and techniques are available that can:

- Determine the required engine performance for a particular vehicle based on the manufacturers required market position and values
- Demonstrate how the car will feel to drive before any hardware is actually available
- Calculate steady state and drive cycle fuel economy taking into account engine efficiency, component friction and control system calibration

This project has developed and applied tools that will meet these requirements. This will aid the petrol engine designer/developer during the concept confirmation phase of a new engine/vehicle programme with the following aspects:

- The engine power and torque
- The vehicle performance with a given engine
- Customer perception of the performance level
- Base engine fuel economy

- Drive cycle fuel economy
- Key base engine geometry such as bore, stroke, bearing size, …
- Key peripheral engine components such as intake and exhaust systems

This is shown in the diagram in figure 1.

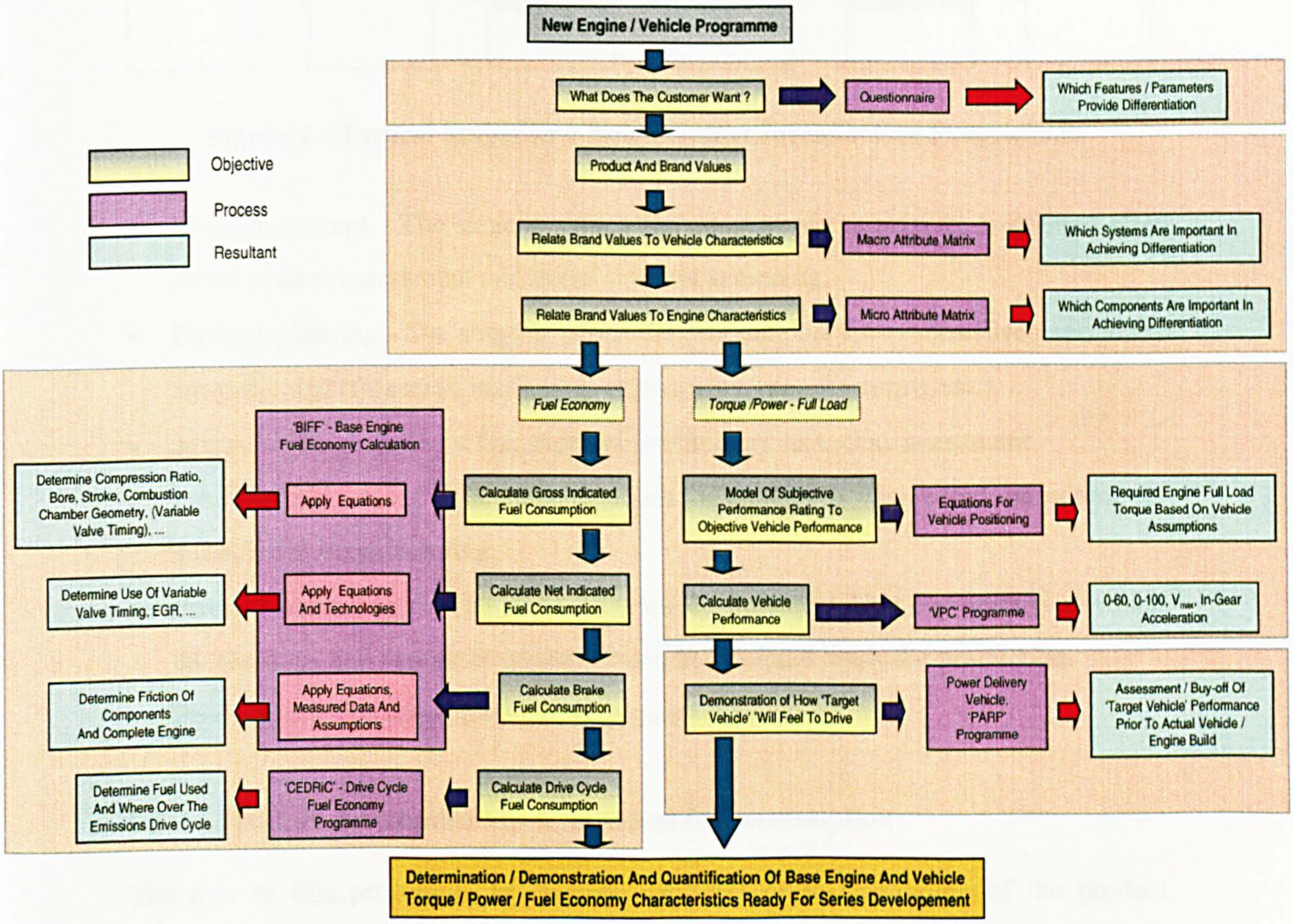


Figure 1 – Overview of the Scope of the Tools Developed to Aid Product Definition

This research will show how I have made it possible for the concept confirmation phase of a new product to achieve improvements of:

- Phase duration reduced by 49%
- Resource requirements reduced by 27%
- Phase cost reduced by 17%

2 New Product Introduction Process

The purpose of the New Product Introduction (NPI) process is to take a product concept through to volume production. The typical stages of an NPI process are shown in figure 2.

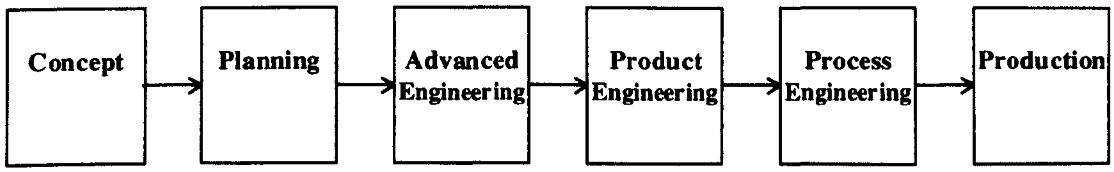


Figure 2 - Typical Stages in a New Product Introduction Programme

- Product concept - The stage at which the concept of the product is defined after initial market assessment and initial concept screening.
- Product planning - The stage at which the product concept is formalised and plans are generated (financial, marketing, engineering, manufacturing etc.)
- Advanced Engineering - The stage for preliminary technical assessment.
- Product Engineering - The stage at which the concept is engineered into a product suitable for manufacturing.
- Process engineering - The stage often called manufacturing engineering at which the facilities and processes are developed and defined ready for production.
- Production - The stage at which the product is produced.

2.1 Product development as a rehearsal for consumption

The role of this process is to increase the level of understanding of the product throughout the stages to increase the suitability of the product for consumption. Each stage adds value to the product as it is becomes increasingly refined based on the information generated and actions taken.

Clark and Fujimoto [1] have considered this idea of each stage adding value through product refinement based on the information generated, in the concept of the development process being a rehearsal for consumption. This is shown in figure 3.

This concept shows the known and accepted linear NPI process of figure 2 but drawn in a different manner, illustrating how the development stages are trying to predict what the actual use or application of the product or process will be. Thus, showing how the product definition should match what the customer will actually want or aspire to, and equally how the other planning and development stages are merely preparation for the final application.

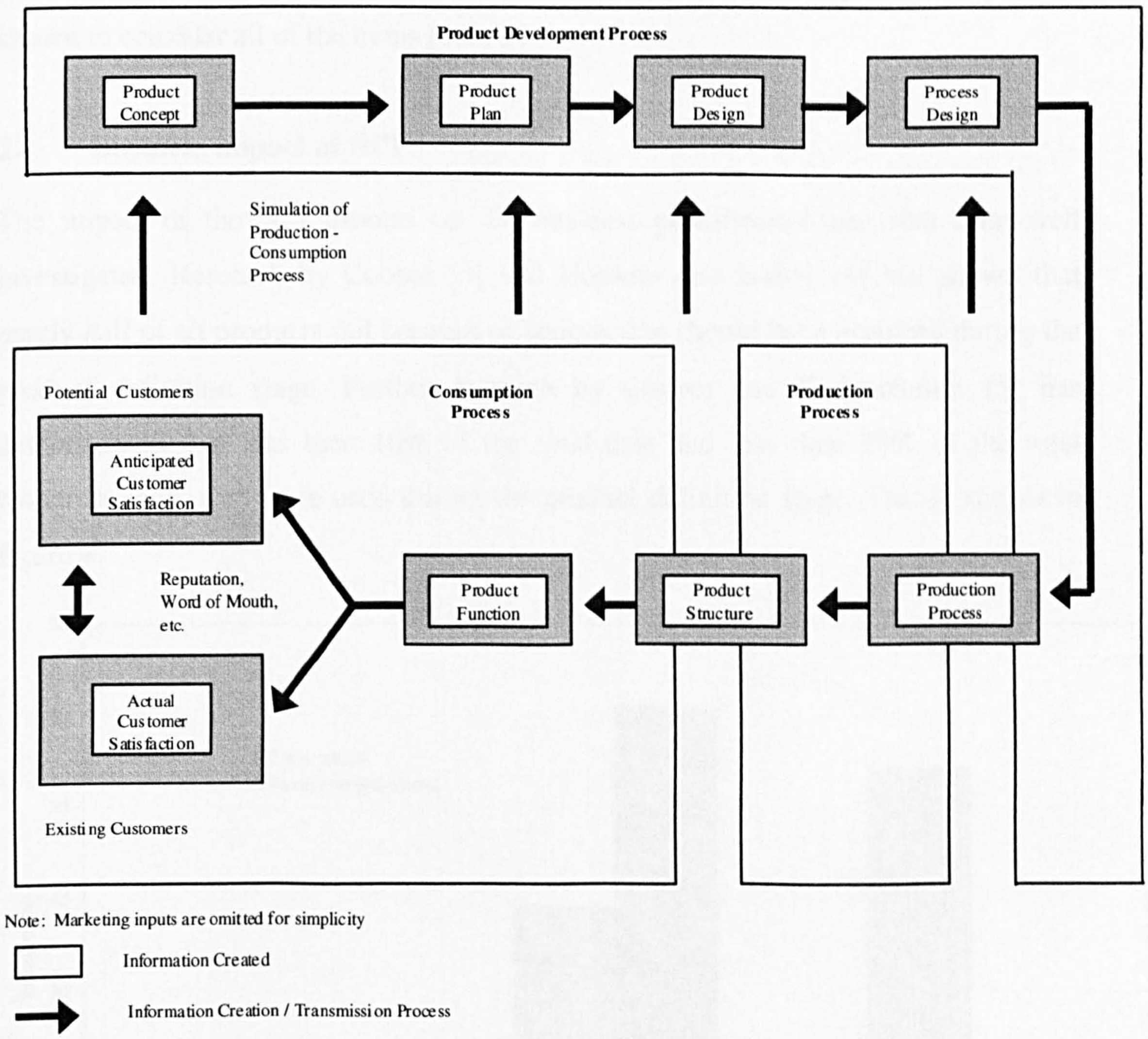


Figure 3 – Product Development Being A Rehearsal For Consumption [1]

The other important factors to consider are the different aspects of the product definition, the objective and subjective. As these factors describe the attributes which need to be included during the development programme. These are [1]:

Objective	What it does:	Performance/technical specification
	What it is:	Outline package and key definitions
Subjective	Who it is for	The target customers
	What it represents	The character and values embodied within it

Failure to address all of these items as is often the case will lead to a lack of competitiveness as the concept will be weak. But successful products have been shown to consider all of the items [1, 2, 3]

2.2 Business impact of NPI

The impact of the NPI process on the business performance has also been well investigated. Research by Cooper [3] and Hopkins and Bailey [4] has shown that nearly half of all products fail because of actions that should have occurred during the product definition stage. Further research by Cooper and Kleinschmidt [5] has demonstrated that less than 10% of the total cost and less than 20% of the total resources employed were used during the product definition stage. This is shown in figure 4.

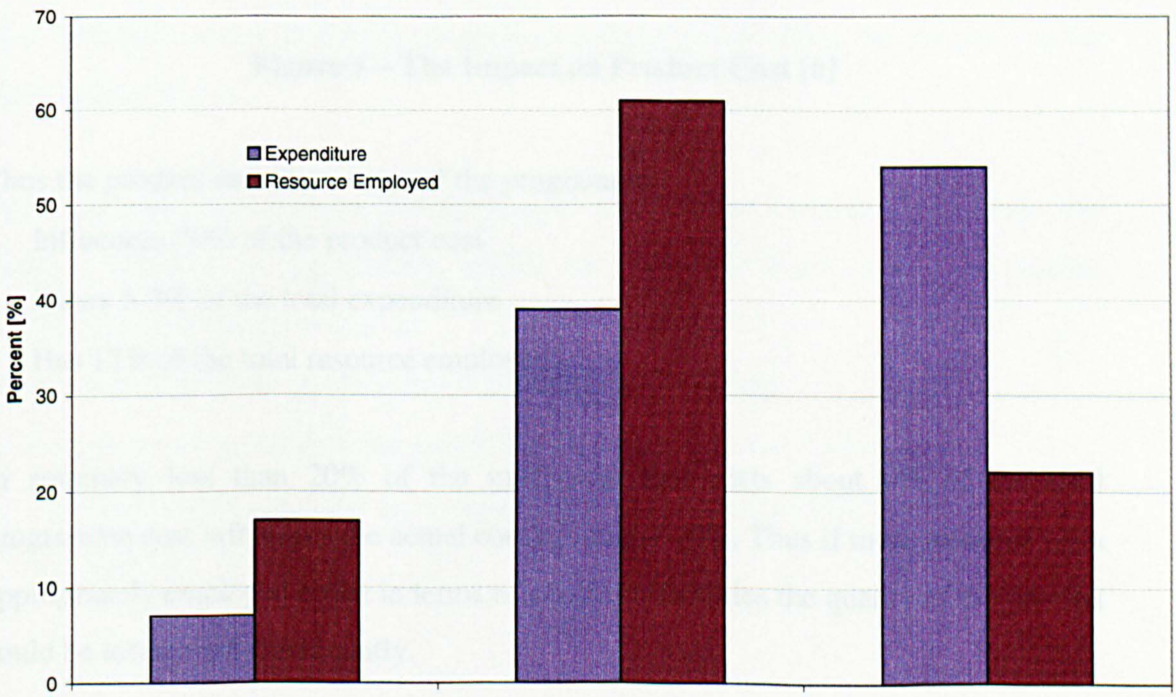


Figure 4 – Comparison of Expenditure and Resource Employed During A Typical NPI Programme [5]

This complements earlier findings of Munro [6] who determined the impact on the actual product cost of the product definition stage. This shows that this has an influence on 70% of the cost yet only accounts for 5%. This is shown in figure 5.

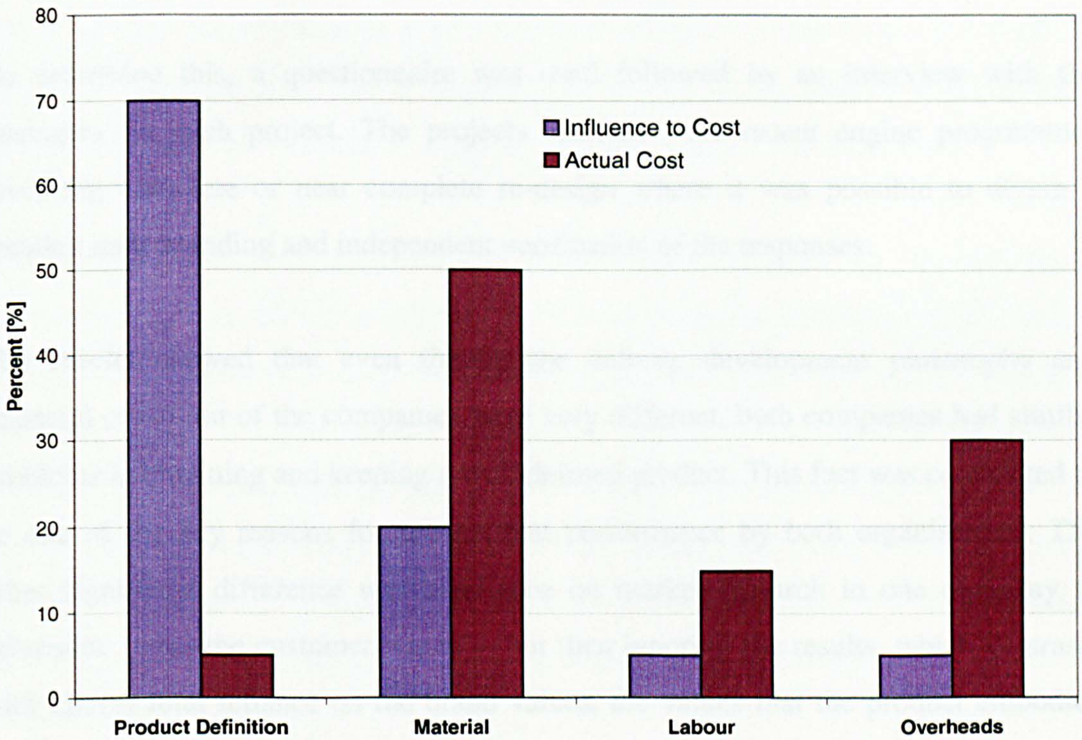


Figure 5 – The Impact on Product Cost [6]

Thus the product definition stage of the programme:

- Influences 70% of the product cost
- Incurs 5-7% of the total expenditure
- Has 17% of the total resource employed

In summary less than 20% of the manpower that costs about 6% of the total programme cost influences the actual cost by around 70%. Thus if more resource were appropriately employed either in terms of people or facilities the quality of the product could be influenced significantly.

2.3 NPI in-practice in the automotive industry

I then conducted further research through the benchmarking of two European Automotive manufacturers. This can be seen in submission 1 chapter 4. This research was conducted to understand what are the shortcomings of the NPI process in practice.

To determine this, a questionnaire was used followed by an interview with the managers for each project. The projects selected were recent engine programmes involving complete or near complete re-design where it was possible to obtain a detailed understanding and independent verification of the responses.

The results showed that even though the culture, development philosophy and financial condition of the companies were very different, both companies had similar problems in obtaining and keeping a well-defined product. This fact was considered to be one of the key reasons for sub-optimal performance by both organisations. The other significant difference was a reliance on market research in one company to determine 'what the customer wants' – but then ignoring the results, which contrasts with almost total reliance on the brand values, the values that the product embodies which differentiate one product from another, with the other organisation. However there was still no way of linking the product definition with either the customer or the brand requirements.

This translation of the brand requirements, into product definition objectives, the tangible elements of the product, within the context of new engine and vehicle development means the ability to:

- Predict the product position based on the product concept
- Develop detailed targets that link to the product objectives / concept
- Allow sensitivity analysis to be conducted at a component level but to understand the high level impact

3 Importance of Product Definition

Research by Cooper [3] has shown that successful products have on average 75% more man hours spent on activities before the start of series development than unsuccessful products. With around 20% of new products failing to reach their predicted sales volume because of poor product definition during the pre-development stages of a programme. This is further justification of the need to employ more resource in the product definition stage where major benefits can be attained.

Further examination of two major European manufacturers (to be known as manufacturer A and B) was conducted in the area of engine selection for the vehicle. This has showed that quite different approaches are used. 'Manufacturer A' had a very detailed plan that followed a text book [2, 3, 4] approach of a structured plan of ever increasing detail. This started with the plans for the vehicle, leading through to the engine (or other major components), then onto the manufacturing and development facilities. There was a tangible link throughout the hierarchy, and a link to the internal and external forces that are acting upon the development environment. This is shown in figure 6.

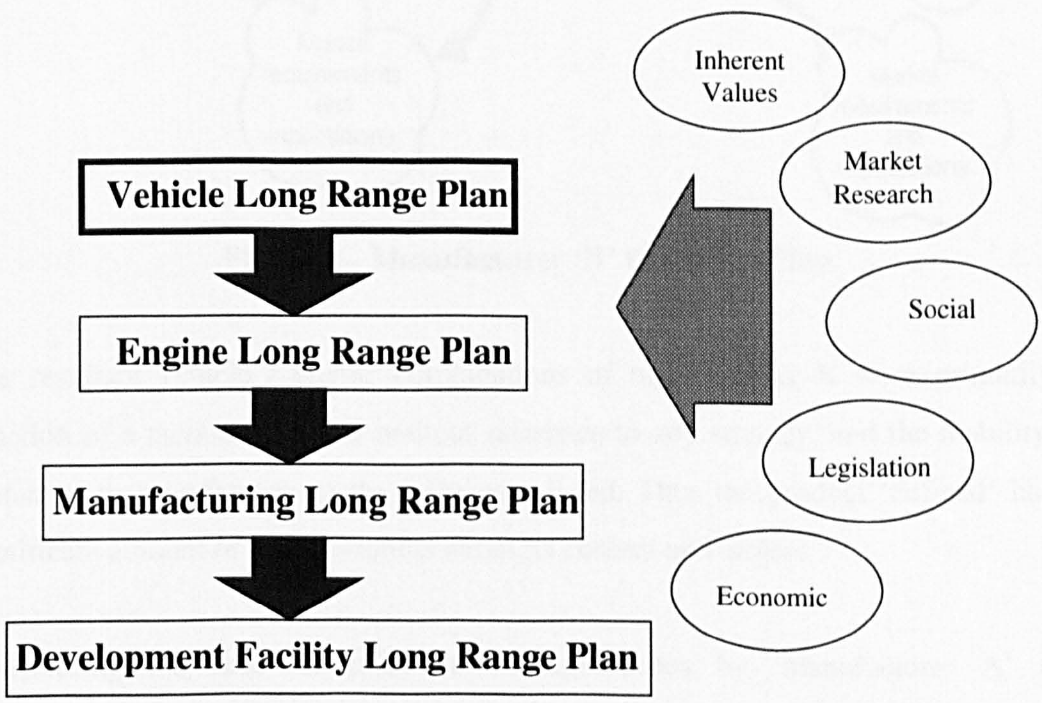


Figure 6 – Manufacturer 'A' Definition Plan

Contrasting with this at the other extreme was 'manufacturer B'. Here the scenario is of various influences being evident which is shown in figure 7. These include:

- Market requirements and expectation
- Availability
- Technology content
- Tactical requirements

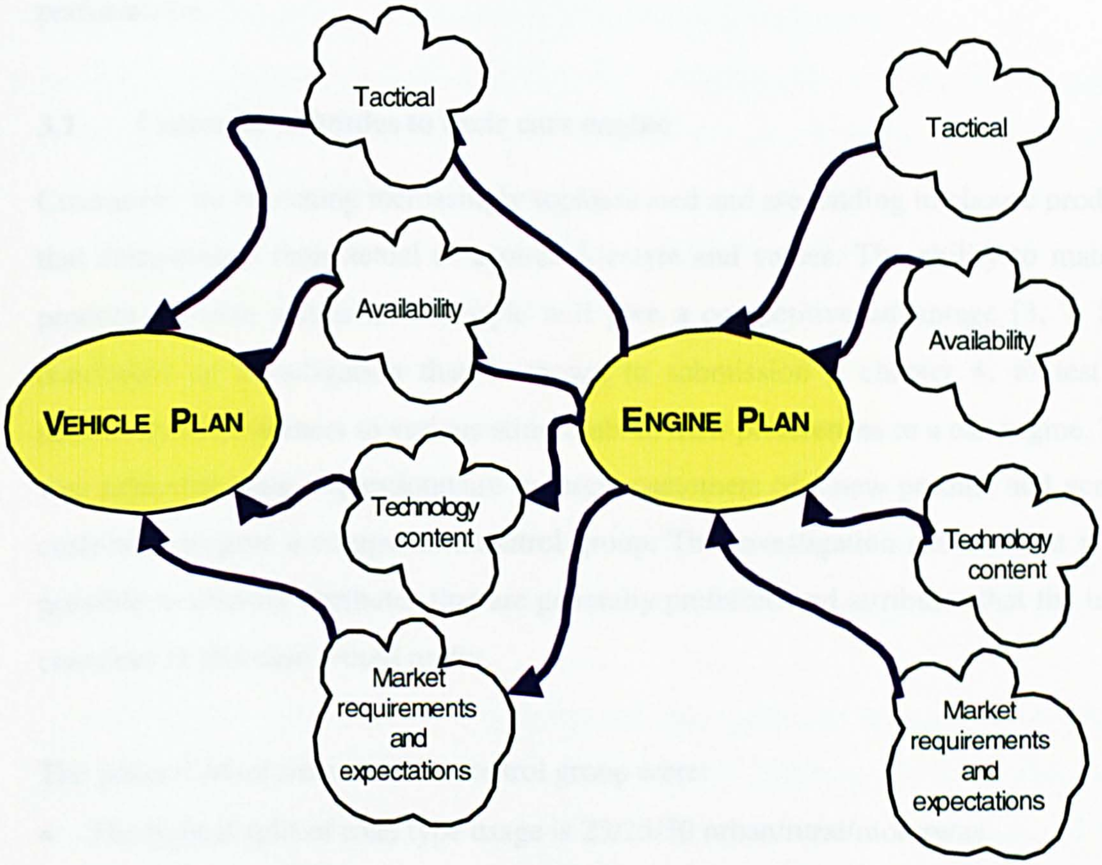


Figure 7 – Manufacturer 'B' Definition Plan

The resultant vehicle / engine combinations of manufacturer B were primarily a function of a tactical response without reference to any strategy, and the inability to match or make reference to the influences listed. Thus the product 'defined' had a significant amount of haphazardness about its content and targets.

Considering the total extremes of the approaches by 'manufacturer A' and 'manufacturer B', the results were very similar with both companies citing lack of product definition to be a major cause of sub-optimal performance. With the structured approach taking too long from the 'signing off' of the product until the start of production, this resulted in late modifications through the change of operating environment and lack of early integration of the component systems that caused conflicts. This contrasts to the 'lack of strategy approach' that fails to meet the customer expectation/needs because the product launched is not matched to these requirements. It can be stated that approaches, from each end of the spectrum, lack appropriate product definition and have caused the shortfall in released product performance.

3.1 Customer attitudes to their cars engine

Customers are becoming increasingly sophisticated and are tending to choose products that complement their actual or aspired lifestyle and values. The ability to match a product to these values and lifestyle will give a competitive advantage [3, 7, 8]. I conducted an investigation that is shown in submission 2 chapter 4, to test the sensitivity of customers to various stimuli about their preferences to a car engine. This was achieved using a questionnaire to target customers of a new product and general customers to give a comparison/control group. The investigation showed that it was possible to identify attributes that are generally preferred and attributes that the target customer in this case would prefer.

The general observations of the control group were:

- The typical split of road type usage is 25/25/50 urban/rural/motorway
- There is a general trend towards wanting positive auditory feedback of the engine behaviour during starting and acceleration.
- Around 65% of the entire sample required their engine to start within 1-3 seconds, with only 20% requiring a faster start. This time is far longer than can be achieved. However, the desire for a consistent start is very high at around 85%.
- Cold idle speed is an area of indifference, however around 70% consider a low hot idle speed to be of importance and it must be quiet.
- The throttle progression should be between linear and sharp during acceleration, with a tendency towards linearity for cruising
- Customers do not know what engine speed they drive their cars at.

- The brochure figures are considered important but an understanding of what they mean is generally low.
- Fuel economy is considered the single biggest issue when considering a vehicle choice for over 50% of the sample, however 0-60 acceleration time was also considered important but by 20% less.

The areas in which the separate group of target customers for a new lower executive car showed a preference and where the behaviour differed include:

- The target customer travelled around 40% more than the average, but the split of road usage was very similar. However, the amount of single occupancy of the vehicle was 20% higher.
- The target customer was on average around 15% more in favour of auditory feedback, particularly during hard acceleration.
- The desire to stay in a high gear was greater, requiring more torque
- Fuel economy does not have a significant effect on the driving style
- The single biggest reason for purchase of nearly 50% of the target customer sample considered was the 0-60 time vehicle choice, however fuel economy was also considered important in this comparison at 35%..

In summary, the investigation showed that the target group in this case wanted things just a little bit better than average with respect to the vehicle power train. This can be seen in the increased desire to maintain a higher gear, the importance of 0-60 acceleration times and the neglect of fuel economy. However it has shown it is possible to differentiate for a target customer by the engine and vehicle characteristics.

The true benefit using abstract questioning to infer the customers desire for vehicle behaviour is questionable. This statement is made as the one overriding observation from this work is that the understanding of what the engine/vehicle does and of certain essential terminology is demonstrably low. It is therefore believed that a method of being able to demonstrate the characteristics would be of considerable benefit to the product definition process for the engine and vehicle.

4 Translation of Subjective Ratings into Objective Engineering Terms

One of the problems that faces the engine development engineer in the product definition stage of the programme is how to translate the ratings that are given during vehicle assessments into objective engineering terms such torque, gear ratio, throttle progression etc. The inability to make this connection will mean there is:

- A huge missing link between what the customer wants and what is engineered, due to the lack of information and the inability to justify many decisions
- Impossibility to test and demonstrate the sensitivity of parameters to customer satisfaction

Two techniques to fulfil these requirements have been considered:

- Quality Function Deployment (QFD)
- Marque Engineering

QFD is the traditional method of associating customer requirements with feature content. This was developed by Mitsubishi in 1972 and taken to America by Ford and Xerox in 1986 [9]. The considered major shortcoming of this technique is that although it provides the link between customer requirements and design features, the high reliance on the customer is considered dangerous. The use of the customer as the centre of the design process means that the resultant product will be heavily normalised to the requirements/opinions of a variety of people and will reflect the views at the point of asking and not when the product will be launched. This may be acceptable for:

- Very high volume manufacturers like Toyota for vehicle manufacture
- Products with short lead-times, for example low end consumer electronics such as personal hi-fi
- Products bordering on being commodities, such as basic white goods like fridges and freezers

However, it is believed to be not necessarily applicable for products such as engines and vehicles where it has been identified a high level of product differentiation is required.

4.1 Marque Engineering

An alternative method is marque engineering, in which the first and unique stage links the attributes that a product with its unique history can embody, with ratings on the importance of individual values to a particular product. Having linked the high level attributes (termed macro attributes which are essentially the behavioural characteristics experienced by the end user) to the brand values that determine the importance of each macro attribute, the results can be ranked and the most important macro attributes in the fulfilment of these values can be identified. Thereafter the system or component variables (termed micro attributes which are the tangible parameters that allow the experience of the macro attribute) can be related to the macro attributes to show the importance and relationship of a detailed component to the fulfilment of a brand value. The association of the brand values to the product attributes results in a differentiated and matched result to the target customer. Rather than trying to be all things to all men. This is discussed in more detail in section 4.2 onwards. The basic technique was proposed by Ali [10] and as part of this project it has been further developed to give a required engine torque, applied to a new vehicle programme and validated from basic vehicle dynamics. The process further developed and applied as part of this thesis is outlined in figure 8 and will be discussed in more detail in the following text and concluded with a detailed overview in figure 14.

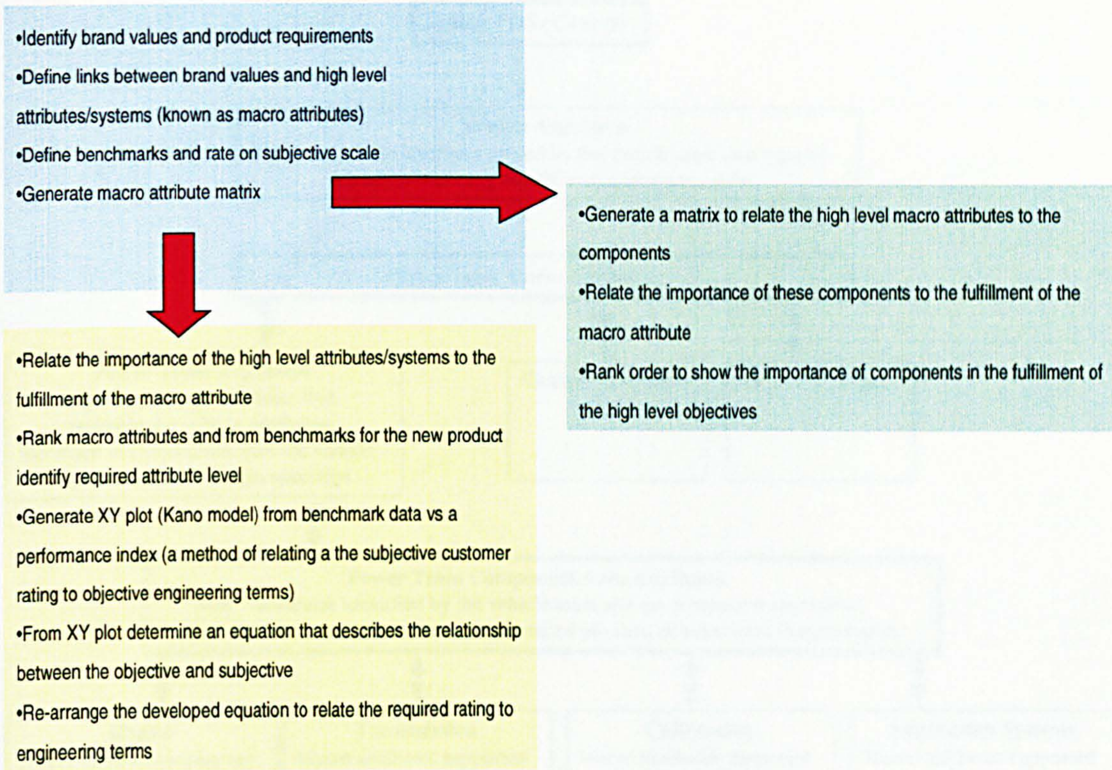


Figure 8 – Outline of Process of Marque Engineering

4.2 Links between vehicle concept and systems: Macro attributes

The first stage is to identify the links between the high-level vehicle concept / statement of objectives with the various component or system groups. This is required so that at a vehicle level it is possible to obtain an overview of how the various factors are connected. Described in submission 2 chapter 7 and shown schematically in figure 9, is the method that is used for the identification of the macro and micro attributes used in the subsequent stages and how they are all linked. The generation of these attributes is proposed to be a combination of experience of the system specialists, competitor assessment and observation of customer use.

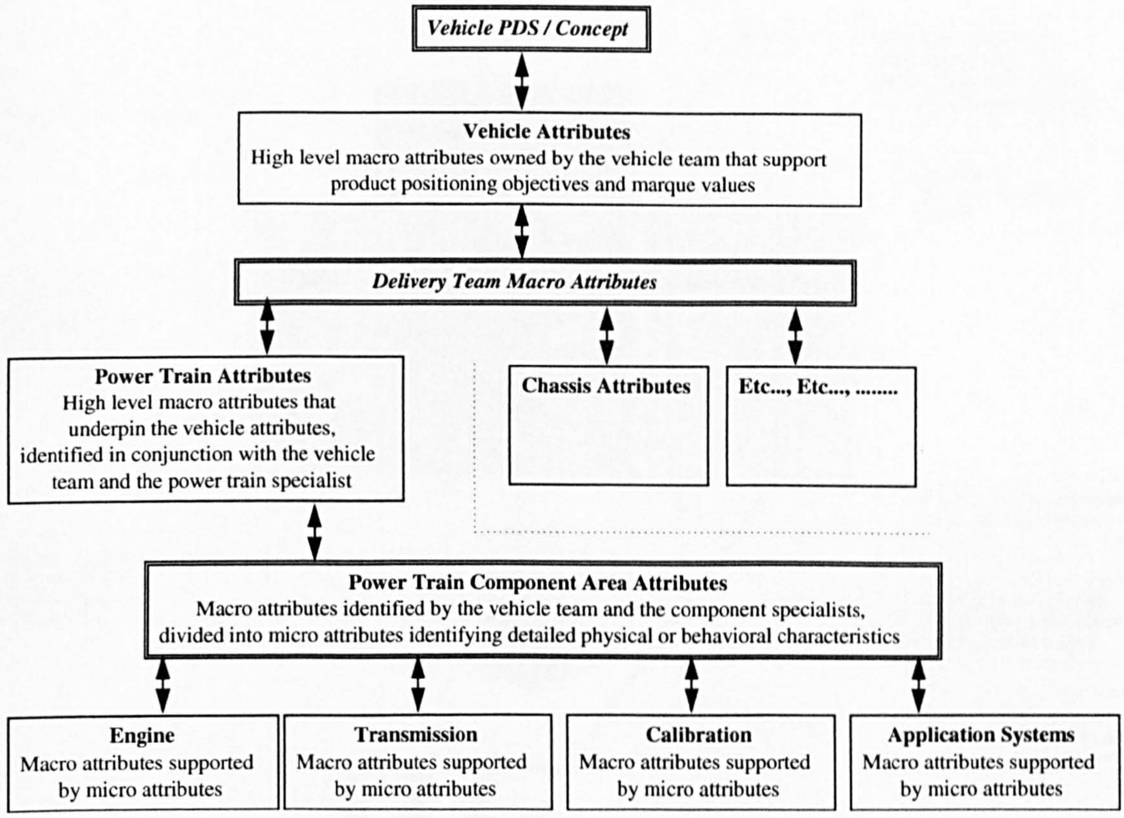


Figure 9 – Overview of the Process Used to Identify the Macro and Micro Attributes

The vehicle concept will have a statement of the brand values and then using the output of the macro and micro attribute identification process, it is possible to construct a matrix relating the strength of the macro attribute to the fulfilment of the brand value. Each macro attribute can have a benchmark vehicle assigned to it, to enable description and to assign a level (an OEM specific rating). Then by involving the vehicle team it is possible to define a weighting of the importance of a brand value to that particular product. The sum of each macro attribute and brand importance is defined as the 'macro attribute importance rating'. By ranking these macro attributes and comparison with the benchmark it is possible to define the desired rating for an attribute. This is shown in figure 10.

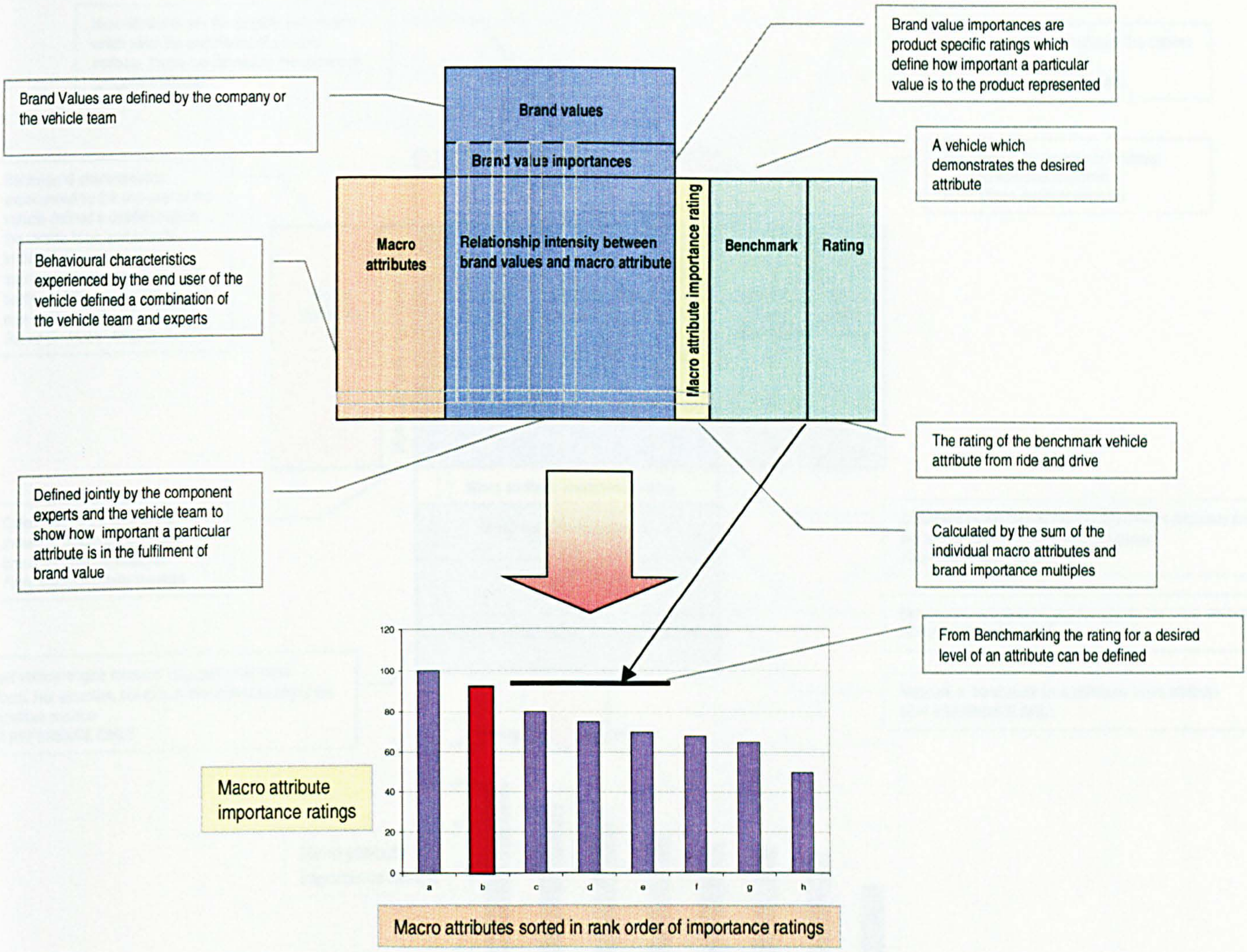


Figure 10 – Process For Macro Attribute Matrix Generation

From the macro attribute matrix the micro attribute matrix is generated with the purpose of giving an indication which system must be considered important in the fulfilment of the brand value.

4.3 Links systems and components: Micro attributes

The micro attribute matrix is constructed in a manner similar to the macro attribute matrix. The macro attributes and their importance identified earlier are related to the system or component attributes – named micro attributes. The intensity of this relationship is then summed as before and plotted in rank order. This is shown in figure 11.

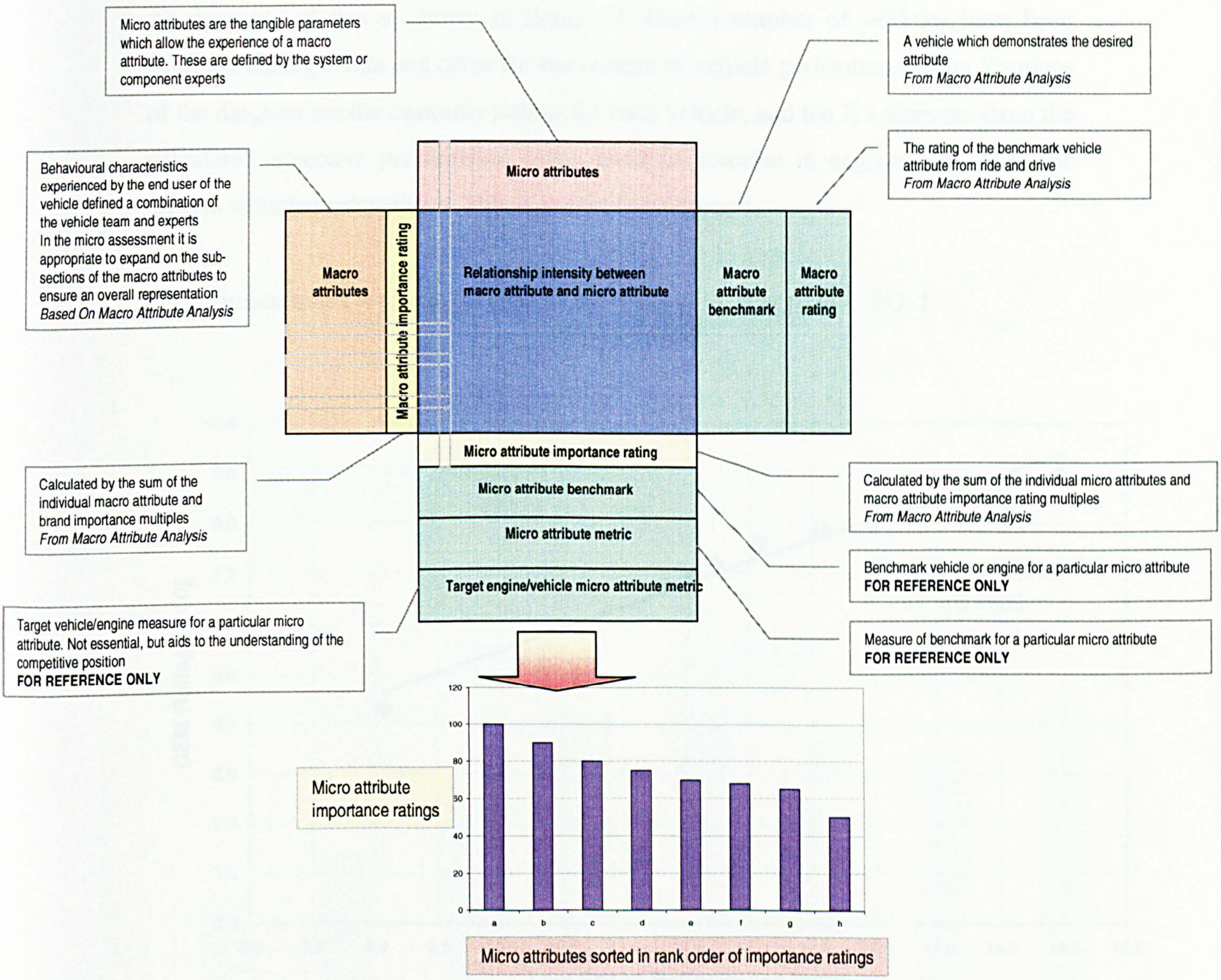


Figure 11 – Process for Micro Attribute Matrix Generation

4.4 Kano model

A Kano model is a method for showing the relationship of objective criteria (what it does) to subjective criteria (what the customer thinks of the product attribute) via an XY graph. The subjective inputs to the graph are the customer ratings from product appraisals using an arbitrary scale, usually a rating from 0 to 10. With an objective value that is related to the behaviour that is being considered, for example vehicle performance being a function of the engine torque, engine speed, vehicle gearing, vehicle weight, drag, etc, this objective value is also known as a performance index.

An example of this is shown in figure 12. Here a number of vehicles have been assessed during a ride and drive for the criteria of vehicle performance. The Y values of the diagram are the customer ratings for each vehicle, and the X values are from the calculated objective performance index used to describe in engineering terms the criteria vehicle performance. This is shown in equation 1.

$$\text{Performance index} = \frac{\text{torque (in a given speed range) x gear ratio}}{\text{vehicle weight}} \quad \text{EQ. 1}$$

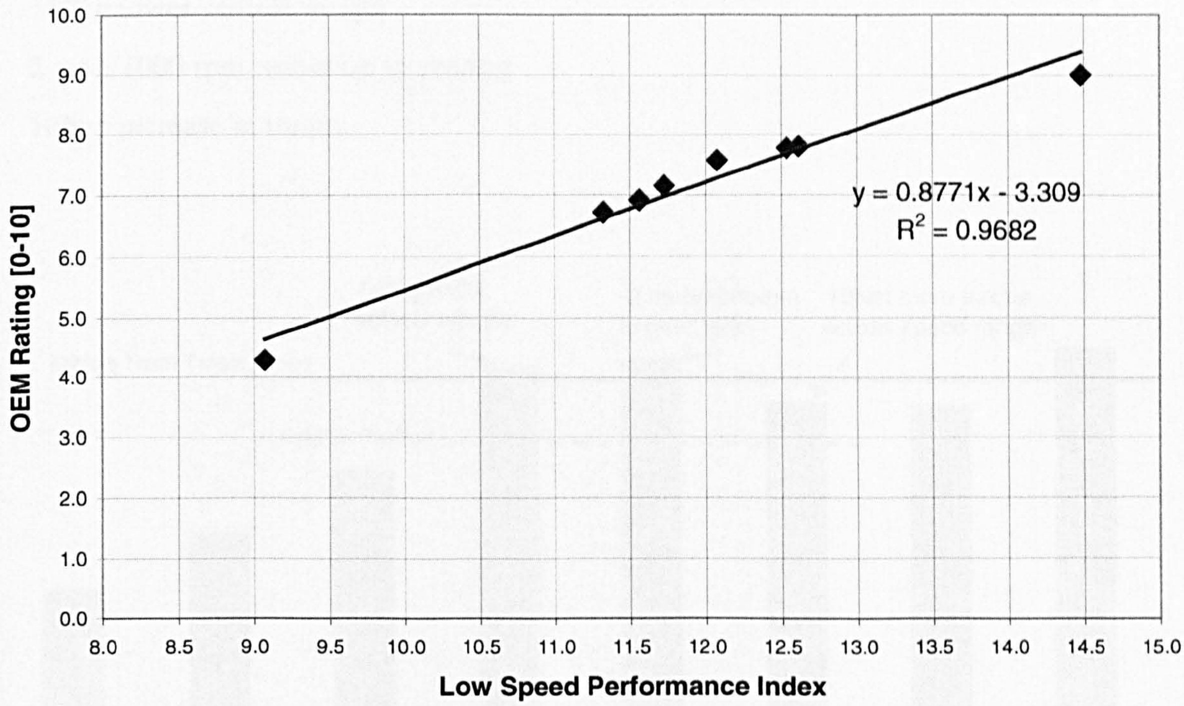


Figure 12 – XY Plot of Performance Index vs OEM Rating

From the equation that relates the subjective to the objective it is possible to:

- Relate the required product position to the brand values through use of macro and micro attribute matrices.
- Relate and test the sensitivity of the engineering attributes required to meet the required customer rating. For example for the case of mid-range vehicle performance: the overall level of torque in a speed range, the vehicle gearing and vehicle weight.

- Derive the performance indices and from the known fixed points/working assumptions, the unknown terms can be calculated.
- Predict how the product will behave without having to actually build any parts.

4.5 Application of the results from a Kano model

Having achieved a good correlation it is possible to test the effect of the variables on the target engine / vehicle compared with the competition. This is shown in Figure 13 where a new vehicle original position is compared with three scenarios:

- 150kg lower vehicle weight
- 2 mph/1000 rpm reduction in gearing
- 10Nm increase in torque

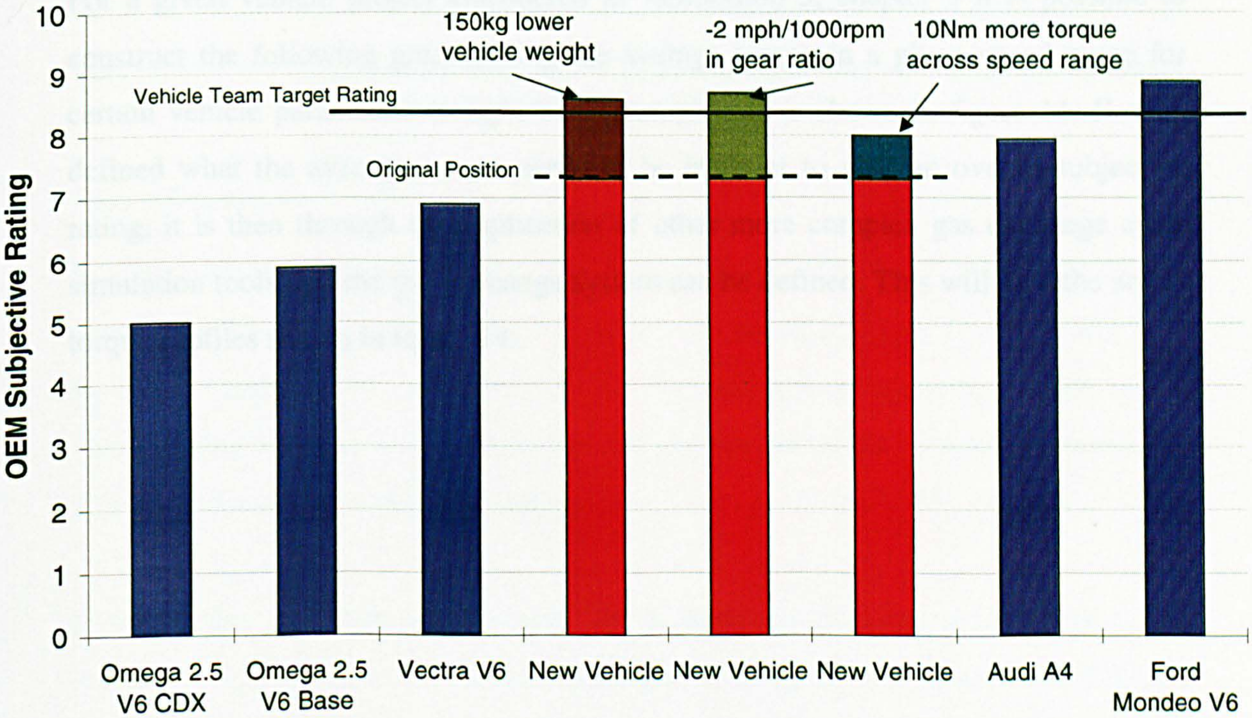


Figure 13 – Comparison of Vehicle Positioning

In this example the vehicle team had set a target rating of 8.5, but the new vehicle could only achieve 7.3. The three cases considered showed that the target positioning could be achieved but would require either a reduction in gearing or vehicle weight.

The reduction in gearing would have a fuel economy penalty which means that a serious task on vehicle weight was required.

Another use of the different performance indices is to define the average torque required from the engine based on a given set of vehicle configuration data: weight, gearing etc. In this example the performance index defined in equation 1 relates the customer perception to the relationship of engine output, gearing and vehicle weight. Through rearrangement of this equation it is possible to determine the torque required in a given speed range. This is shown in equation 2.

$$\text{Torque Nm (in a given speed range)} = \text{Performance index} \times \text{Vehicle weight} \times \text{Gearing} \qquad \text{EQ. 2}$$

For a given vehicle project considered in submission 3, chapter 3 it is possible to construct the following graph giving the average torque in a given speed range for certain vehicle parameters (weight and gearing), this is shown in figure 14. Having defined what the average torque needs to be in order to give an overall subjective rating, it is then through the application of other more complex gas exchange cycle simulation tools that the gas exchange system can be defined. This will give the actual torque profiles shown in figure 14.

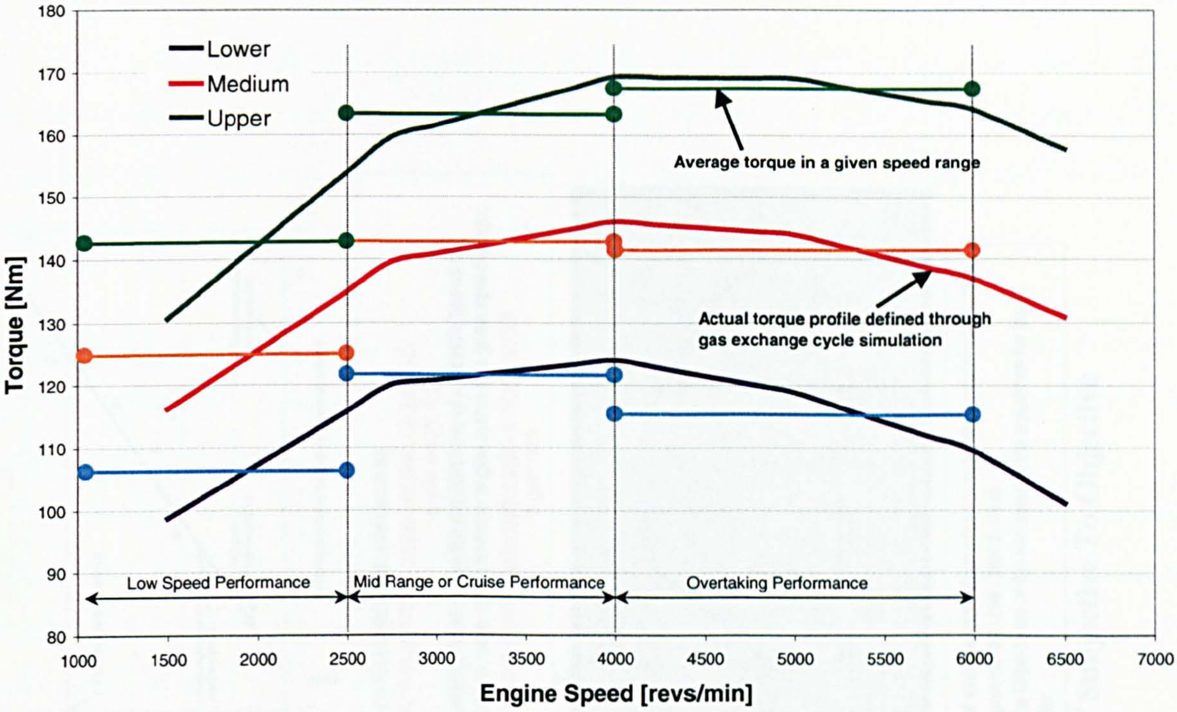


Figure 14 – Development of Engine Torque Curves to Give a Required Customer Rating for Different Vehicle Specifications

4.6 Summary

In summary it has been shown it is possible to link the high-level vehicle values and required customer rating, through a series of matrices (macro and micro) and equations (performance indices) to give a required engine torque in a speed range. This can then be used with more traditional tools to define the detailed characteristic. This overall process is shown in figure 15.

It should also be noted that although the development has occurred entirely on the aspect of engine performance the same techniques are proposed for use with different attributes.

PAGE MISSING IN ORIGINAL

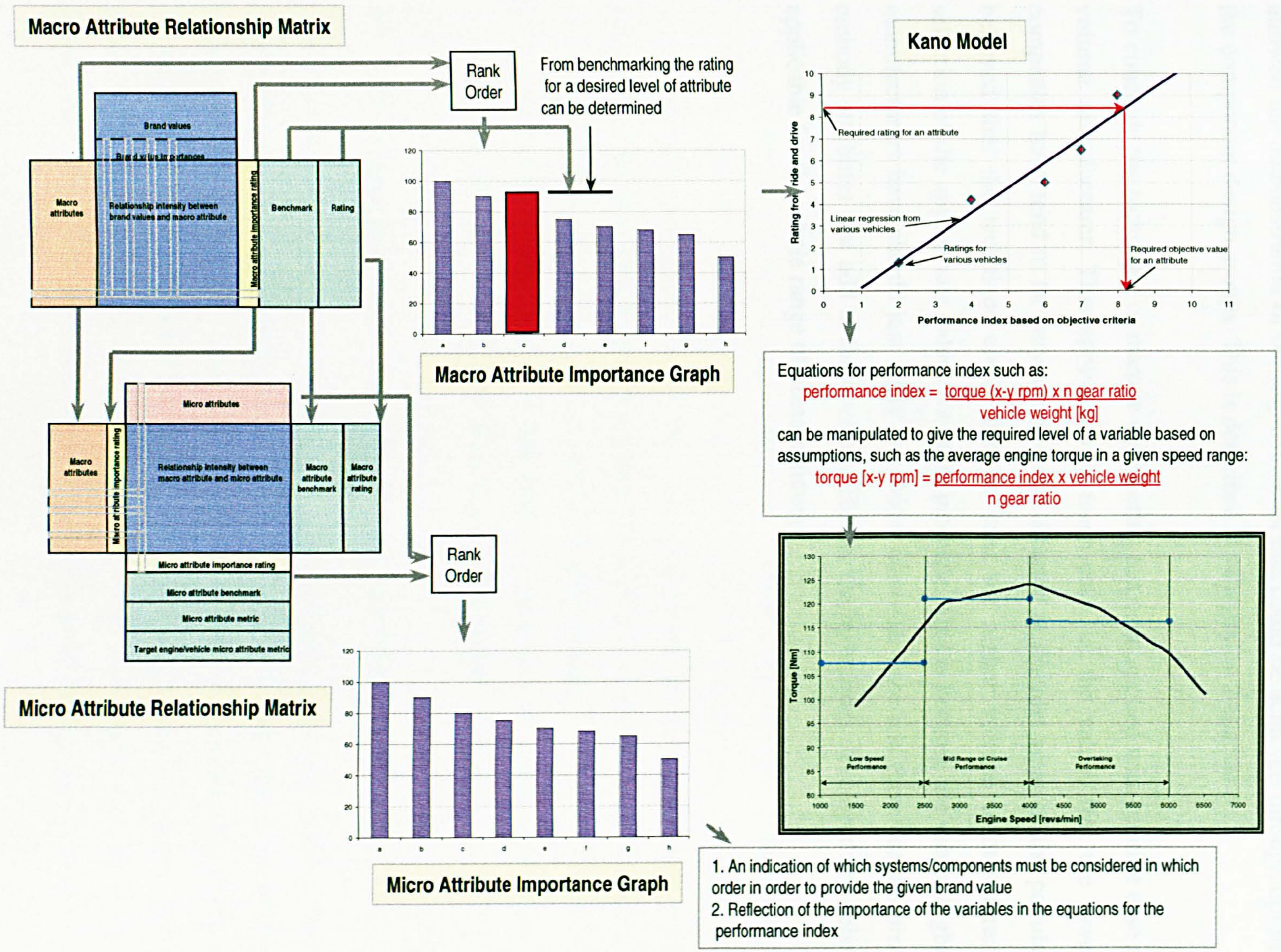


Figure 15 – Overview of the Process For Translation of Subjective To Objective

This technique has been verified through calculations based on the vehicle dynamics and practically on a new vehicle and engine programme in the area of full throttle performance of the engine and vehicle. The technique was also used for prediction of the product position and allowed the demonstration of the improvements that could be achieved through optimisation by the component design groups. This is described in submission 2 chapter 6.

To conclude the technique of marque engineering has been applied with relative ease to a lower volume manufacturer. This application is made easy, as the values that the lower volume companies have tend to be very specific and directed at discreet areas of the population. It is believed that the technique could also be used for higher volume manufacturers through selection of the appropriate values for these products. This is because the values higher volume manufacturers have should just apply to a wider customer base and therefore the product must embody attributes that add to these values. Hence, the techniques developed are believed to be applicable for the whole range of manufacturers.

5 Demonstration of Engine Performance

It has been shown that it is possible to identify the detailed attributes that are important in emphasising the brand values. One of the most important attributes identified was that of power delivery and the techniques discussed will allow the prediction of the required full load performance to fulfil a product positioning relative to the competition. However, what is difficult is the subsequent evaluation or demonstration of the identified, aspired or resultant performance.

This section will discuss how I developed, validated and applied a vehicle known as the performance simulation vehicle to enable the simulation of a new engine/vehicle before real hardware is available. This tool is necessary:

- To allow the driver-feel to be evaluated before any 'real' hardware is available. This allows a continued focus within the project team on design rather than manufacture and build.
- To enable the overall product concept with respect to the engine-in-vehicle performance to be 'bought-off' at the earliest possible stage of the programme. This allows for many iterations to be considered at the time in the programme when it is still time and financially viable. This allows focus on delivery rather than on numerous hardware iterations.
- To enable the what-if studies to be considered and evaluated.
- To add extra correlation data to the models created and to provide a medium for easily generating new models due to the extra degrees of freedom available.

5.1 Development of the performance simulation vehicle

The concept is based on the manipulation of a donor engine output (an engine whose output is greater than that to be simulated) to match what a target or predicted engine would achieve. This manipulation is achieved by controlling the output of the donor engine through the limiting of the airflow into the engine using the throttle, but maintaining or controlling to a defined throttle progression. The vehicle will drive as if powered by the 'new' engine and enable the objectives listed earlier to be achieved. This is shown for a single speed example in figure 16.

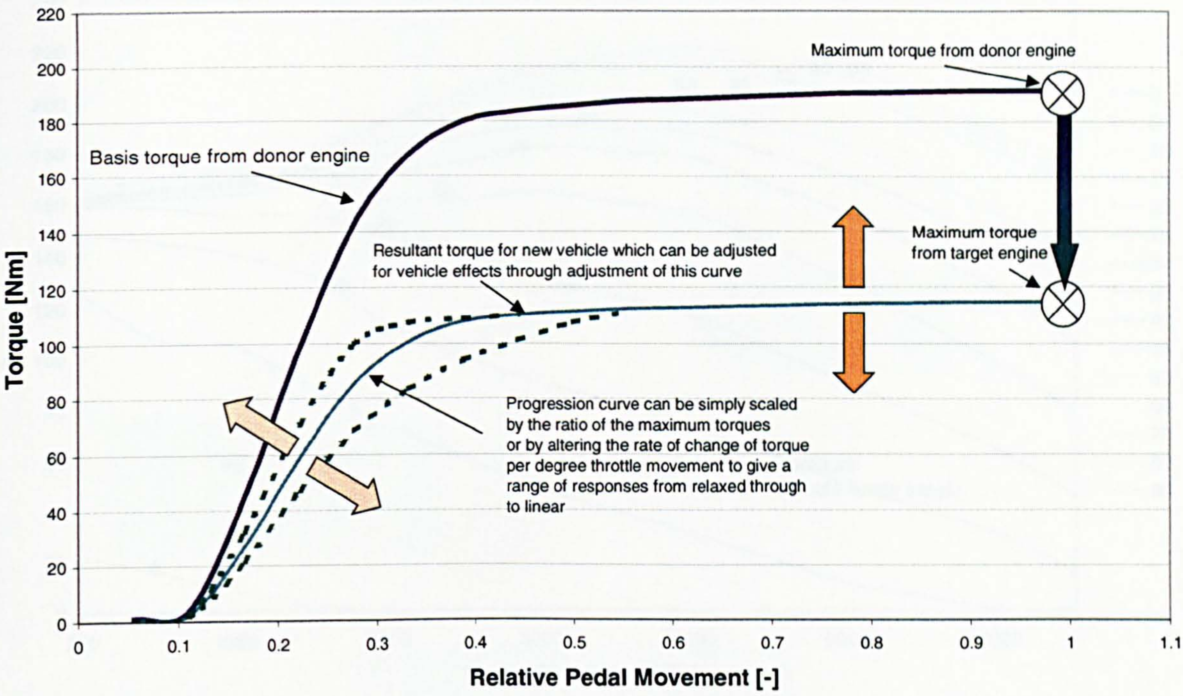


Figure 16 – Modification of donor engine output to match target engine

As the application of this tool was to be on a new engine programme with a capacity range of 1.6 - 2.0l, a donor engine of 2.5l was chosen. This engine was fitted to an engine dynamometer where a detailed map, over 1000 datapoints, of engine output was measured. This gave the information of what is the exact engine torque at a given throttle angle and is shown in figure 17.

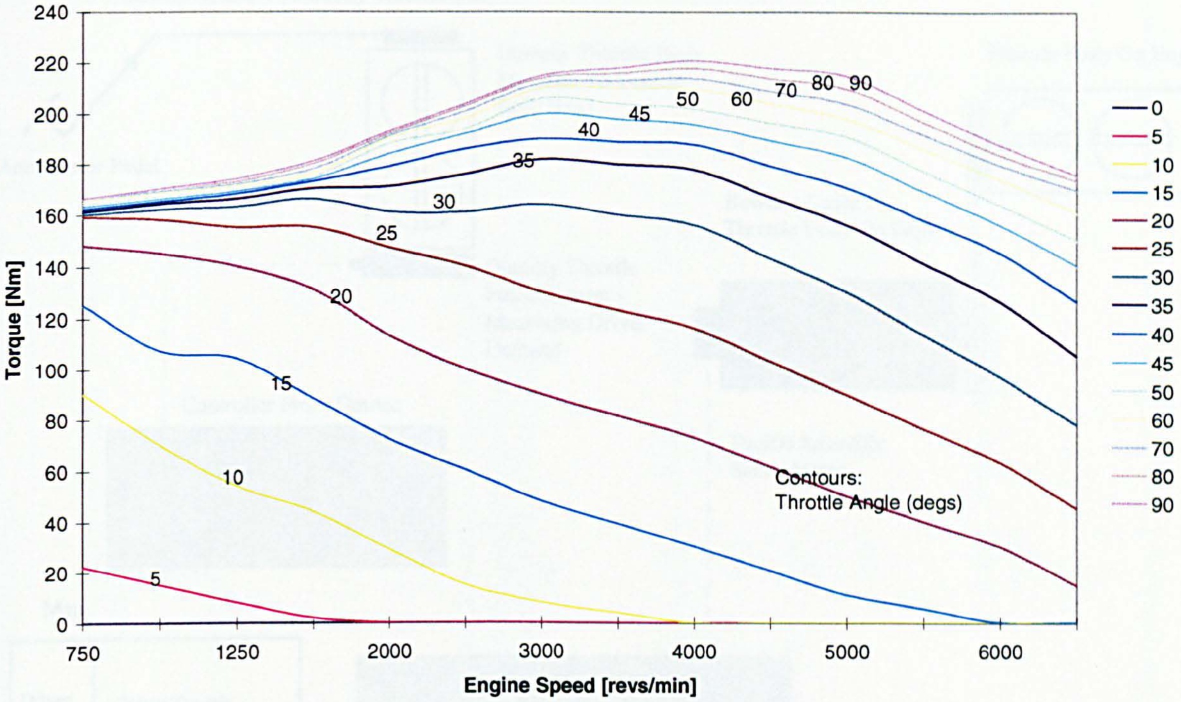


Figure 17 – Output from Engine on Test Bed

A simulator vehicle was built with the 2.5l engine and with an additional control module to regulate the throttle action to simulate the target engine. It was decided that either a separate 'drive-by-wire' module needed to be integrated into an existing engine management system or another unit was to be used so that all the existing elements of the calibration could be carried over and as such give good driveability. The former solution was favoured but not allowed due to internal constraints, so a secondary control unit solution was sort through a third party.

This system shown in figure 18, uses a fixed link to a dummy throttle body where a potentiometer measures the driver demand. The driver demand is then inputted into a controller which maps driver demand against output throttle angle which has been calculated to simulate the new engine, and will be described later. The output throttle angle is converted to a voltage and drives a servo motor that is connected to the engine throttle body.

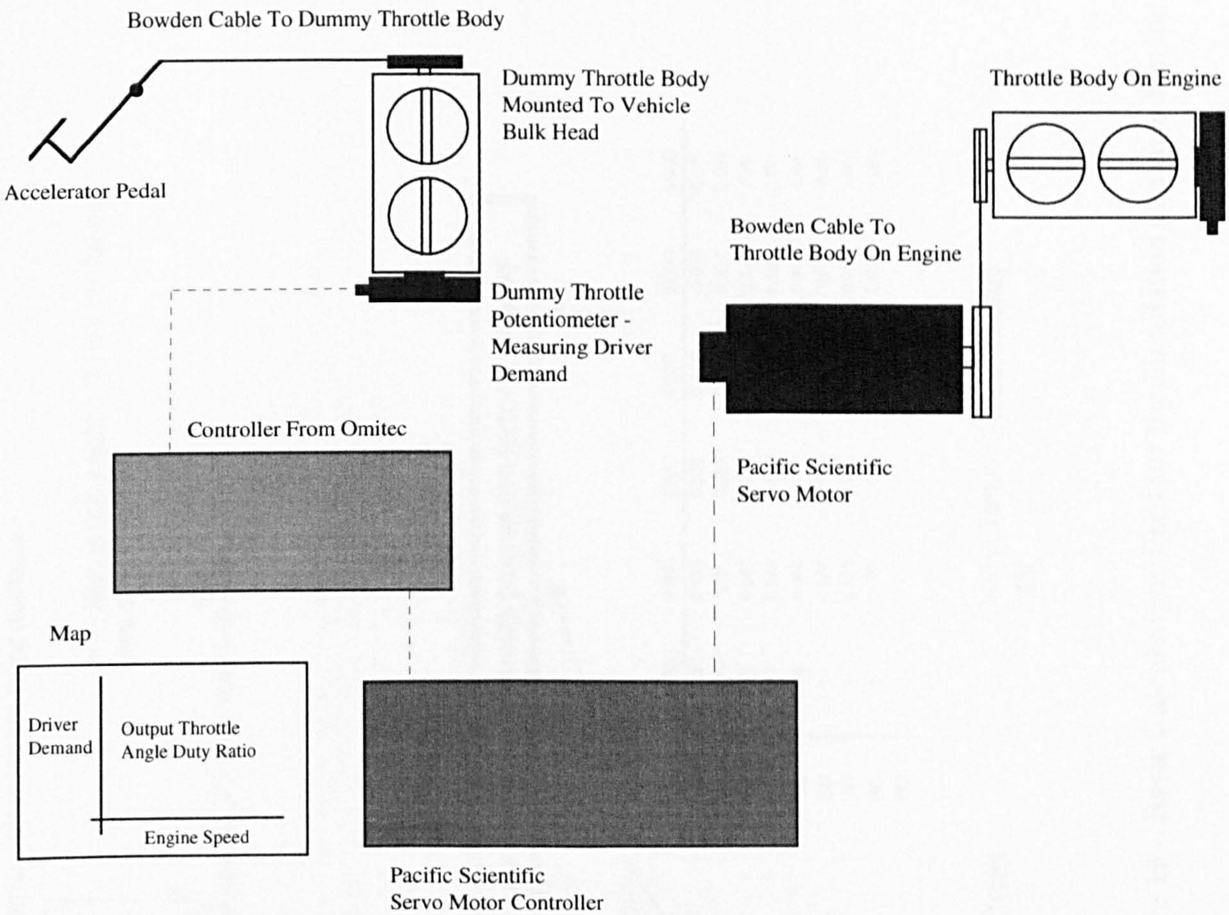


Figure 18 – Overview of Control System

Using a program I wrote named PARP (PerformAnce deliveRy demonstRation Program), the calculation for the required throttle position to give a target level of torque is made. This is detailed in submission 2 chapter 8. The target level of torque is a function of the required full load torque, the throttle progression chosen and vehicle information such as target weight, gearing and aerodynamic drag. This is shown in figure 19. The output from this calculation is used as the map for the main throttle controller. From this information it is possible to simulate a concept vehicle with a concept engine fitted and feel how it will drive.

Vehicle

	Base Vehicle	Target Vehicle
Mass [kg]	1336	1336
Cd [-]	0.32	0.32
Frontal Area [m^2]	1.67	1.67
1st gear [mph/1000 rpm]	6.5	6.5
2nd gear [mph/1000 rpm]	9.5	9.5
3rd gear [mph/1000 rpm]	13.4	13.4
4th gear [mph/1000 rpm]	18.8	18.8
5th gear [mph/1000 rpm]	22.8	22.8

= (Target Vehicle rolling resistance + aerodynamic) + (Base Vehicle rolling resistance +

= 1 - <u>Base vehicle weight</u> X Required full load torque

= Required full load torque X Δ Resistances X Vehicle weight effect on

Engine Inputs:

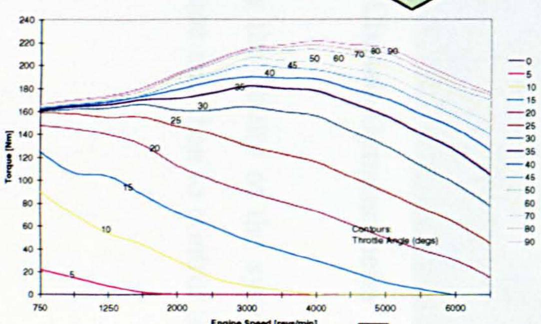
Required Full Load Torque

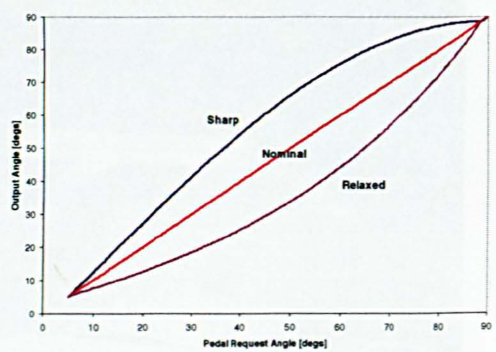
Speed [rpm]	1000	2000	3000	4000	5000	6000	7000
Torque [Nm]	110	140	155	165	150	134	110

Required Throttle

Torque for Target Vehicle = Corrected required full load torque X Throttle progression factor X Relative

Look up throttle angle of donor engine





Throttle Progression Factor = <u>Required Throttle Progression</u>

	1000	2000	3000	4000	5000	6000
10	0.51	0.175	0.079	0.027	-0.018	-0.119
20	0.875	0.6	0.384	0.265	0.207	0.099
30	0.96	0.887	0.739	0.632	0.589	0.49
40	0.97	0.944	0.875	0.788	0.802	0.741
50	0.98	0.956	0.917	0.889	0.938	0.87
60	1	0.967	0.938	0.915	0.97	0.96
70	1	0.978	0.959	0.944	0.988	0.983
80	1	0.989	0.981	0.972	0.994	0.988
90	1	1	1	1	1	1

Relative Torque = <u>Torque at throttle angle</u>

Input throttle angle	Throttle angle of donor engine
	Engine

Figure 19 – Basic Calculations Used for the Simulation of a New Engine

5.2 Validation of the performance delivery simulation vehicle

Having defined the concept, built the vehicle and developed the simulation methodology the next stage was to check that the vehicle with a target engine profile behaved in a manner similar to the predictions (prediction in this context is the vehicle performance predictions determined by two independent calculation programs). This was achieved through a validation process on a chassis dynamometer and on the test track. The objectives of the validation were to determine answers to the following:

- At a constant engine speed is the torque at a given throttle angle what it should be
- At a constant input throttle angle is the torque at a variety of engine speed what it should be
- During traditional vehicle performance tests does the vehicle behave as predicted

The first two stages of the validation are conducted using a chassis dynamometer. The test vehicle fitted to the dynamometer is shown in figure 20.

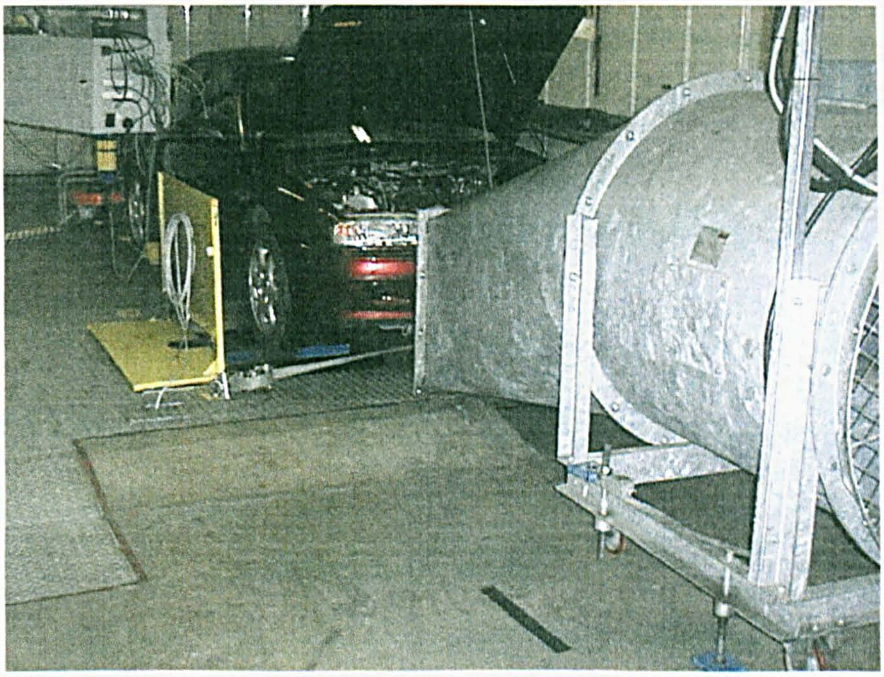


Figure 20 – Vehicle During Test on Chassis Dynamometer

The first stage of the validation process was to verify the ability of the system accurately to define the required throttle angle for a given target torque and then to control to it. The test for this was throttle angle sweeps (from closed to fully open and back to closed) at 4 different engine speeds with 3 different target engine profiles loaded in the controller.

The results were very promising and showed on constant speed operation the correlation of target to measured values was within ±3% from a range of predicted/target outputs in all cases. An example of the results is included in figure 21.

The next stage of the test was at a constant target throttle angle and with varying speed. The condition chosen was to simulate a full throttle power test. Again 3 different engine profiles were loaded and the results presented are typical of all the tests. Figure 22 shows that with the exception of a single engine speed the results fall within the required tolerance of ±3%.

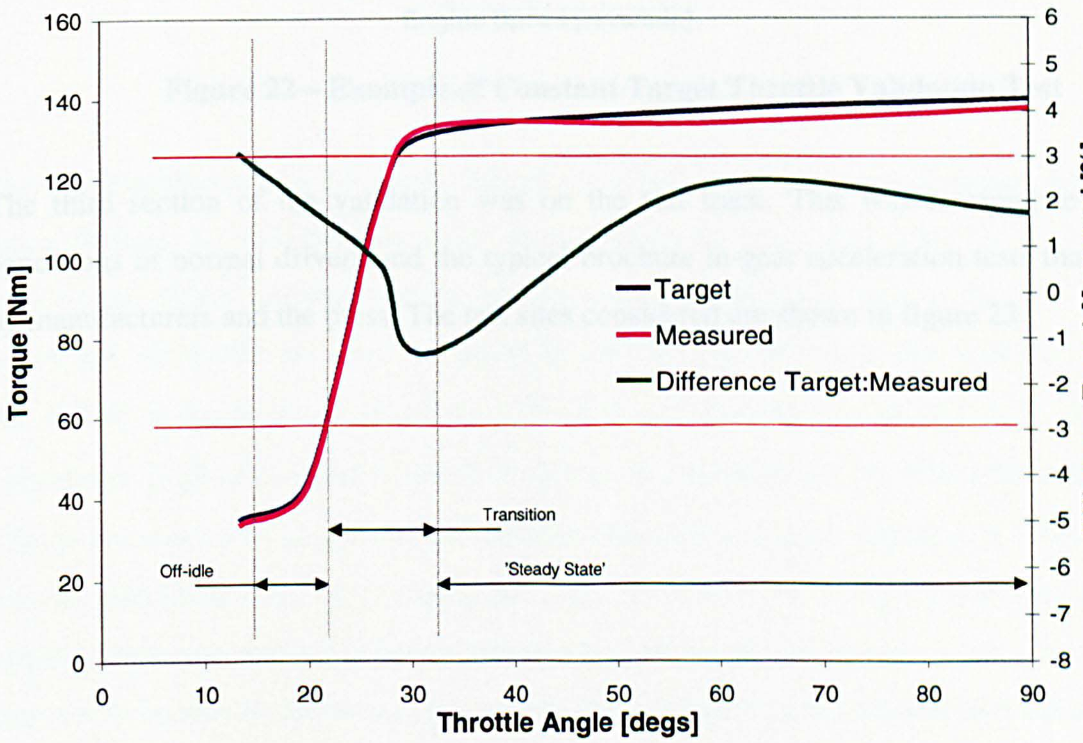


Figure 21 – Example of Constant Speed Validation Test

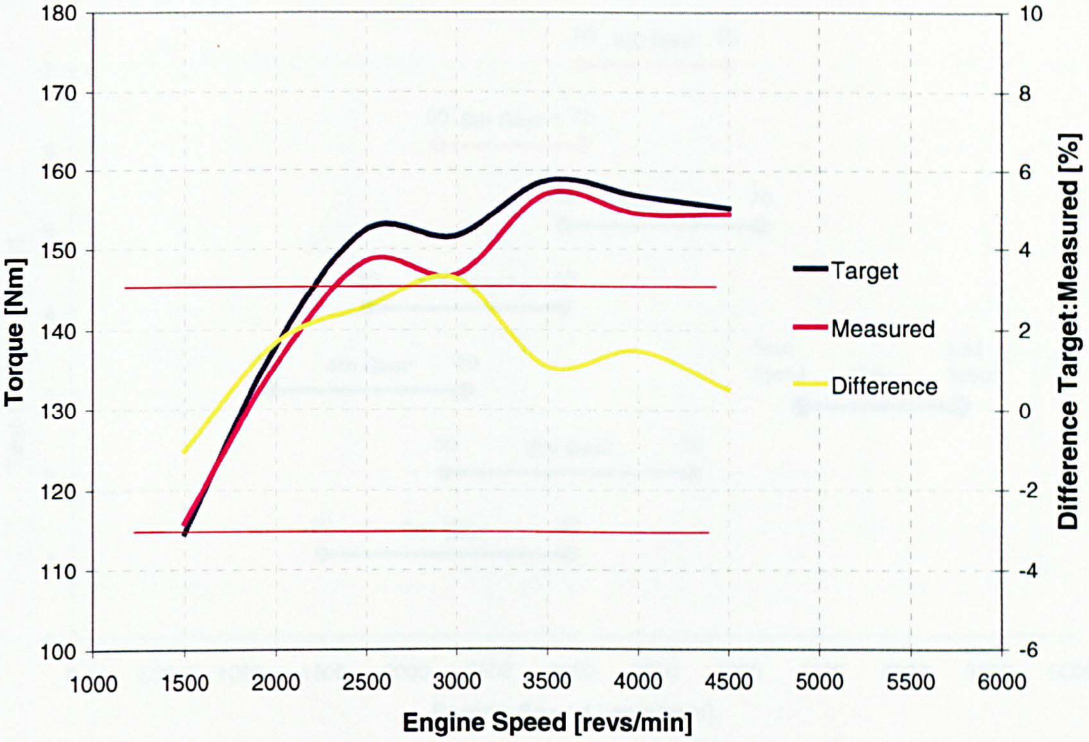


Figure 22 – Example of Constant Target Throttle Validation Test

The third section of the validation was on the test track. This was to simulate the driving conditions of normal drivers and the typical brochure in-gear acceleration tests that are quoted by manufacturers and the press. The test sites considered are shown in figure 23.

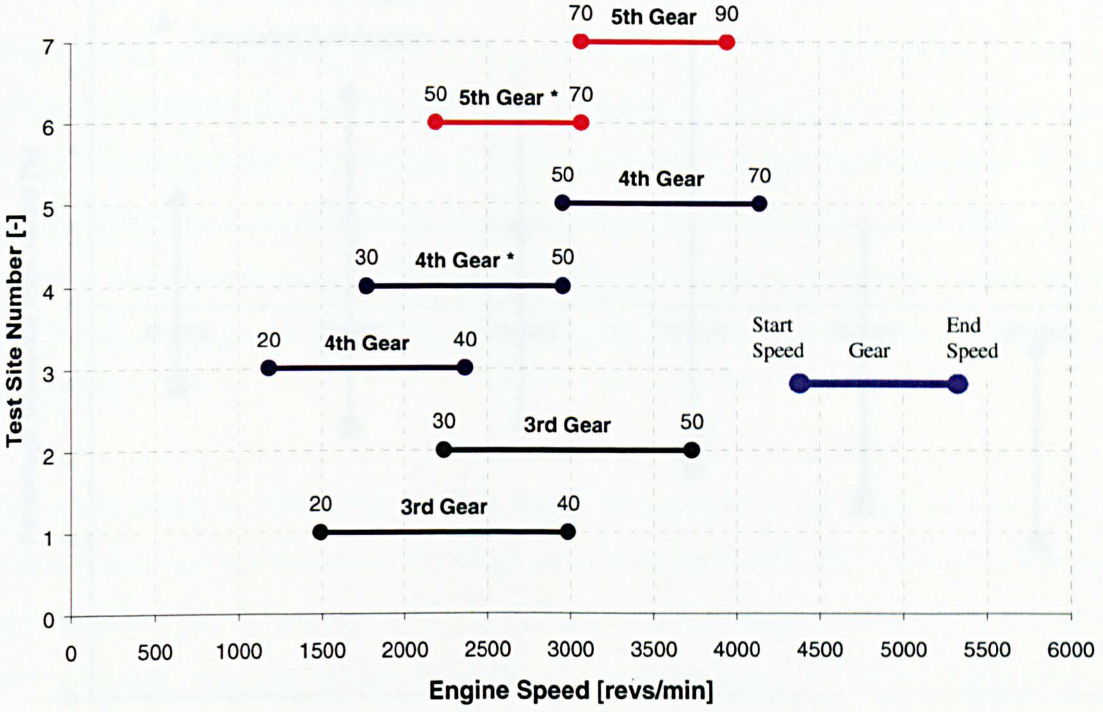


Figure 23 – Test Sites Considered For Vehicle Evaluation

The track assessment is the most difficult on which to obtain accurate results because of the extra degrees of freedom that exist when testing on track and with the vehicle open to atmosphere. Three different vehicle profiles were considered at each of the test sites detailed above and the results are shown in figure 24 and 25. The tests show that in terms of percentage the spread is in the range of –8 to +7%, although the mean is around ±4%. When this is considered in absolute terms a spread of –1.3 to +0.5 seconds is seen, with a mean ±0.3 seconds. This is believed to be acceptable for the demonstration of a target engine in a vehicle during the product definition stage of a programme. This is because the changes considered are normally relative, with comparisons between options being the norm and because it takes a skilled vehicle assessor to be able to determine the absolute level of performance without instrumentation.

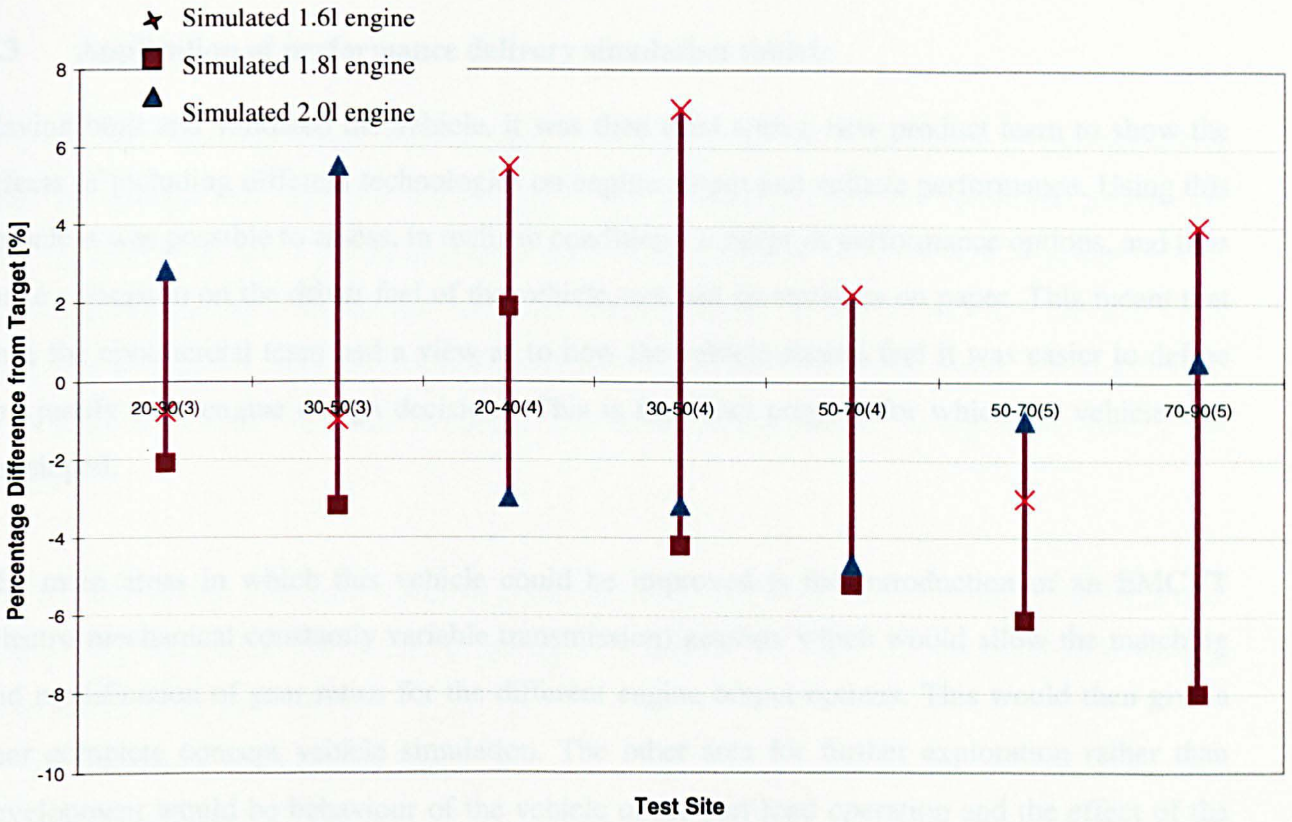


Figure 24 – Track Test: Percentage Error

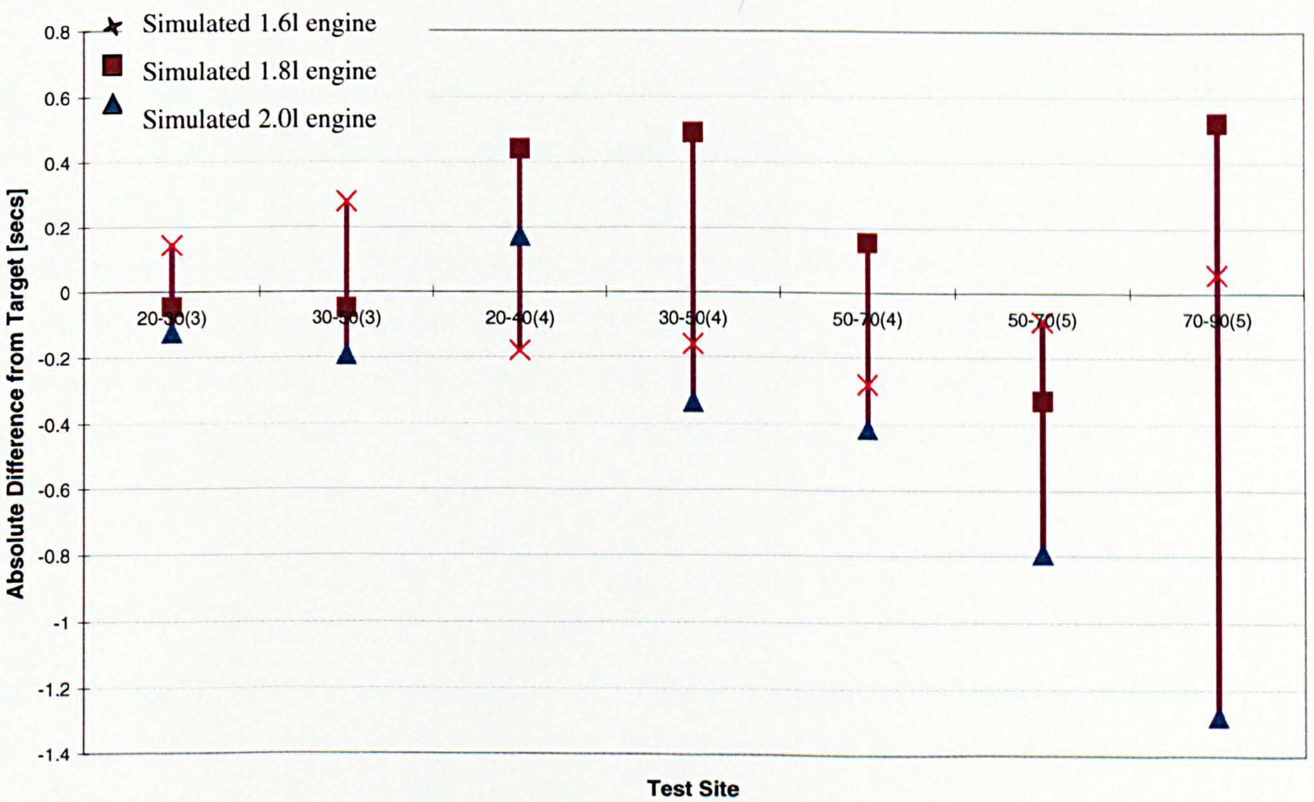


Figure 25 – Track Test: Absolute Error

5.3 Application of performance delivery simulation vehicle

Having built and validated the vehicle, it was then used with a new product team to show the effects of including different technologies on engine output and vehicle performance. Using this vehicle it was possible to assess, in realistic conditions, a range of performance options, and thus make a decision on the driver feel of the vehicle, not just on statistics on paper. This meant that once the commercial team had a view as to how the vehicle should feel it was easier to define and justify base engine design decisions. This is the exact purpose for which the vehicle was developed.

The main areas in which this vehicle could be improved is the introduction of an EMCVT (electro-mechanical constantly variable transmission) gearbox which would allow the matching and modification of gear ratios for the different engine output options. This would then give a near complete concept vehicle simulation. The other area for further exploration rather than development would be behaviour of the vehicle under part load operation and the effect of the throttle progression.

6 Fuel Economy

The previous sections have demonstrated a technique for the translation of the subjective customer ratings into objective engineering terms, and applied this to engine and vehicle full load performance. Another very important area of development is that of fuel economy. This is becoming increasingly significant with the threat of fiscal penalties for vehicles with poor economy and the increase of Government taxation on fuel [11] which means the customer is very likely to start to view fuel economy as a differentiating factor through economics if not ethics.

As fuel economy is becoming a serious issue for automotive manufacturers the ability to predict steady state and drive cycle fuel economy is essential. In order for the prediction of fuel economy to be of use it must:

- Be based on sound assumptions
- Be appropriately accurate
- Allow for detail changes to be made and enables an understanding of the end result

The level needed in this case is relative not absolute, as during the product definition stage the ability to understand the effects of individual small changes is more important than absolute accuracy. The sound assumptions are required to enable simulation of what is really occurring to the engine and not as is often the case generalised overall correction. With the ability for detailed changes to be understood being fundamental during the product definition stage. It is at this stage of a engine/vehicle programme that the basic engine configuration needs to be established and targets set for the various systems that will determine the actual fuel economy of the product.

6.1 Background

The prediction of fuel economy is based on the ability to calculate the elements that will effect the steady state and in-vehicle conditions and the subsequent engine behaviour, taking into account factors of the following three discreet areas:

- *Combustion and thermodynamic:*

  limit of compression ratio and relationship of specific heats

  variable specific heats

dissociation

in-complete combustion

heat transfer to the cylinder walls

exhaust valve opening before BDC

pumping loss

- *Friction losses*

losses due to component friction and electrical loading of alternator

- *Calibration (control of engine fuel and ignition) effects*

modification of engine operating point based on warm-up

fuelling and ignition corrections based on operating point

The amount of fuel used to create useful work output and its resultant energy balance can be characterised for a typical engine in figure 26 [12]. This is shown at a steady state speed and a load-operating condition representative of the European drive cycle. This shows the useful work and the losses that occur in the transfer from fuel energy, also shown are the various efficiencies that are often quoted. Note that due to the dynamic influence of the calibration, this is not considered in this steady state comparison.

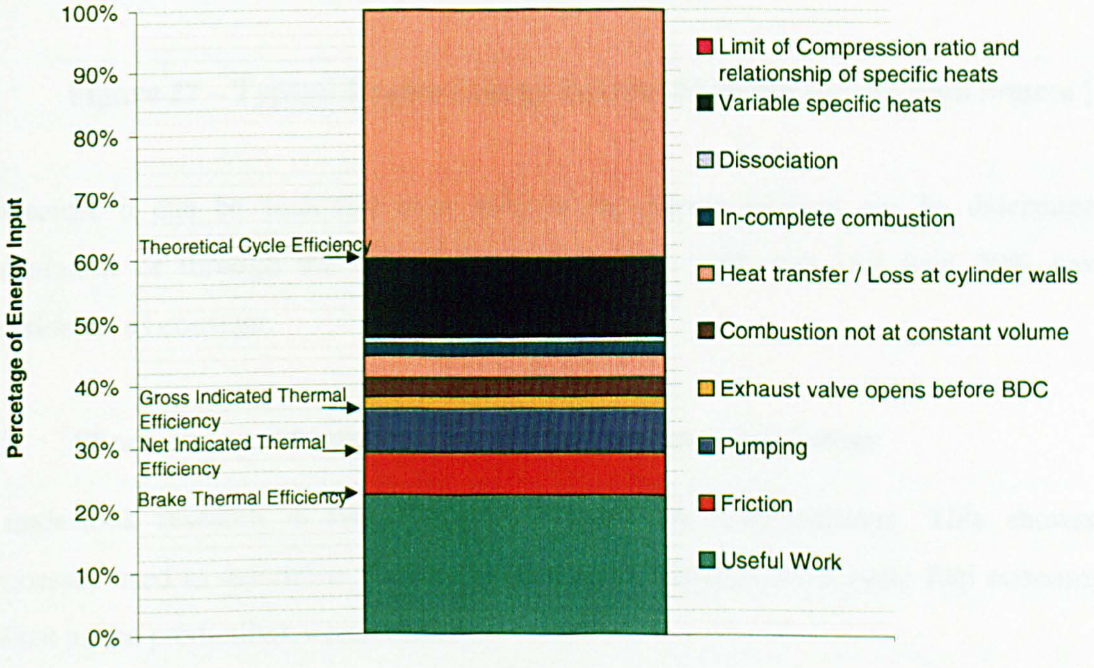


Figure 26 – Typical Engine Energy Balance [12]

These factors can be grouped based on their sources of information, these being:

- Through calculation
- Assumed constant
- Use of benchmark data

The graph in figure 26 can be replotted with different colours to represent the information source. This is shown in figure 27.

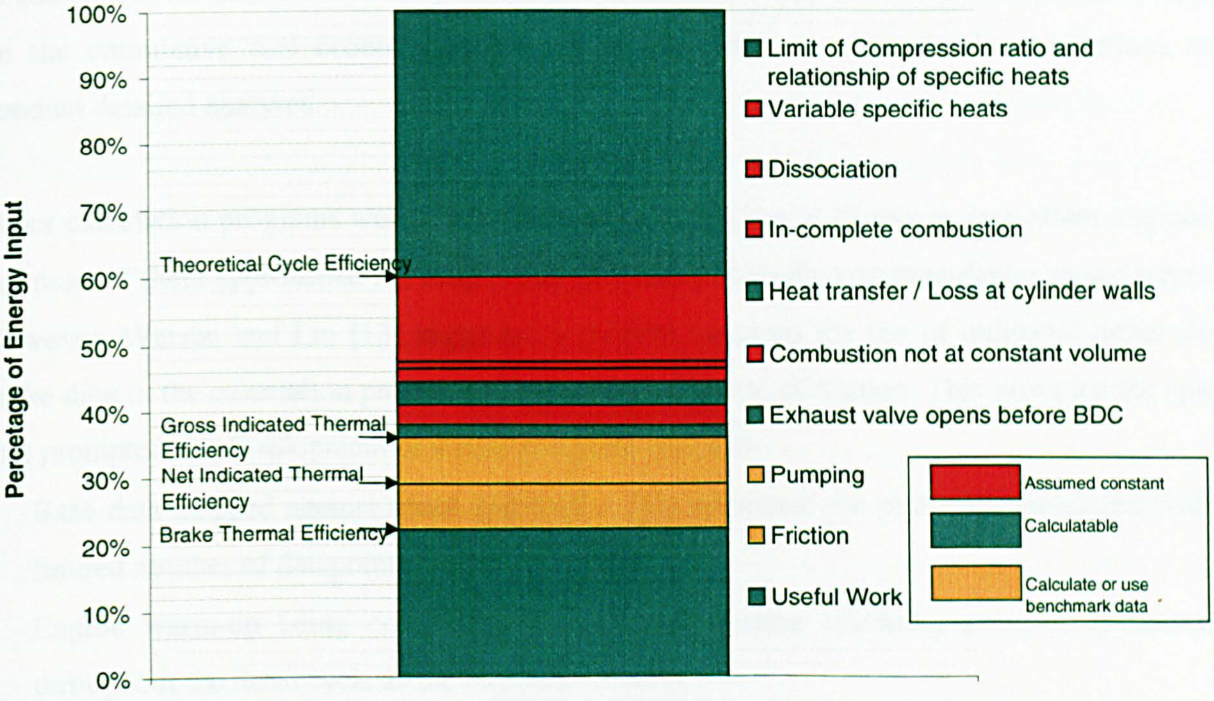


Figure 27 – Typical Engine Energy Balance Showing Information Source [12]

Therefore it can be seen that over 80% of the energy balance can be determined through calculation or through the use of benchmark data, with just less than 20% having to be considered as constant.

6.2 Shortcomings of existing tools for fuel economy prediction

I undertook research in two European Automotive manufacturers. This showed that the processes used to determine the steady state and emissions drive cycle fuel economy were not robust as the predictions were based on:

- A small numbers of measured data points for new technologies

- Best case results not representative of full operating range
- Friction improvements always considered, but the effects of engine geometry changes ignored
- Incorrectly modelled warm-up with the high dependence of friction on oil temperature not considered
- Calibration terms such as idle speed setpoint, warm-up fuelling, etc. were not considered.

In addition to the above it was not possible to determine the effects of detail component changes on the cumulative fuel economy, making it is impossible to understand contributions and conduct detailed analyses.

Other calculation programs were considered from various major European consultant engineers but none of them approached the subject any differently from the two manufacturers considered. However, Watson and Liu [13] suggested a method based on the use of indicated rather than brake data in the calculation process to remove the influence of friction. This provided the spark that prompted the development of a suite programs that had:

- Base data mapped against speed and load – This overcame the problems associated with a limited number of datapoints
- Engine warm-up being considered – The actual engine operating point is represented throughout the drive cycle as the engine warms up.
- Base fuel economy presented in indicated values with further maps of friction and pumping loss – This separated the effects of friction and pumping
- Calibration effects considered that modify the engine operating point of the fuel used – The actual engine operating point in terms of load is effected by calibration as this will alter the idle setpoint, and the fuel and ignition used.

6.3 New techniques for fuel economy prediction

I have developed two programs for fuel economy prediction, BIFF: ***Base engIne Friction and Fuel economy*** and CEDRiC: ***Component based fuel Economy Drive cycle under Realistic Condition.*** These programs have the same structure based on figure 27 where the actual engine operating point is calculated based on a series of assumptions and behavioural characteristics, and linked with the output of BIFF used as one of the inputs for CEDRiC.

BIFF enables the brake fuel economy to be determined through the calculation of the friction and pumping loss and a derived/assumed gross indicated fuel economy as shown in figure 26. This gives the benefits of:

- Being able to follow the route to the calculated brake specific fuel consumption (bsfc) through clear and accepted stages
- Giving visibility of targets for friction, gross thermal efficiency, ... which can be monitored discreetly during the development process, as the factors which effect them are normally the responsibility of different departments
- Showing the effects of discrete component changes that can be understood and quantified
- Forcing the movement away from glib and unsubstantiated statements as every statement or assumption can be monitored and quantified.
- Allowing an input to a drive cycle program so the assumptions made here can be followed through to an in-vehicle situation

The program BIFF has not been validated as such as all of the calculations made are based well-recognised equations. The innovation has been in the application of these known equations in a commercial environment and not in the generation of new relationships. However, confidence is high as it has been successfully used for auditing of a new 4 cylinder engine and prediction for a new 6 cylinder engine as discussed in submission 2, chapter 7.

The purpose of CEDRiC is to determine the actual engine operating condition during the emissions drive cycle. It takes the output maps from BIFF with additional characteristics of:

- Fluid warm-up profiles
- Friction effects due to oil temperature
- Calibration effects of idle speed control, after start enrichment and coolant/oil temperature trims
- Vehicle weight, gearing, drag, ...

By then conducting time steps throughout the drive cycle at the required vehicle speed and actual engine work the real fuel used at the operating point is determined. This is then summed to determine the fuel used over the cycle.

Confidence in the accuracy of the calculation has been obtained through comparison of measured data with prediction of existing vehicles and with 'adjusted' calculations for new products by an automotive manufacturer. The level of accuracy determined was for the worse case within 6%. Which although not accurate enough for absolute terms without adjustment, it is suitable for the relative sensitivity studies to gain a insight into where to focus the development and to decide which components or technologies should be included. Also with further work or adjustment it is believed to be possible to improve absolute correlation with measured data.

An overview of the steady state and drive cycle fuel economy calculation process and interconnections are shown in figure 28.

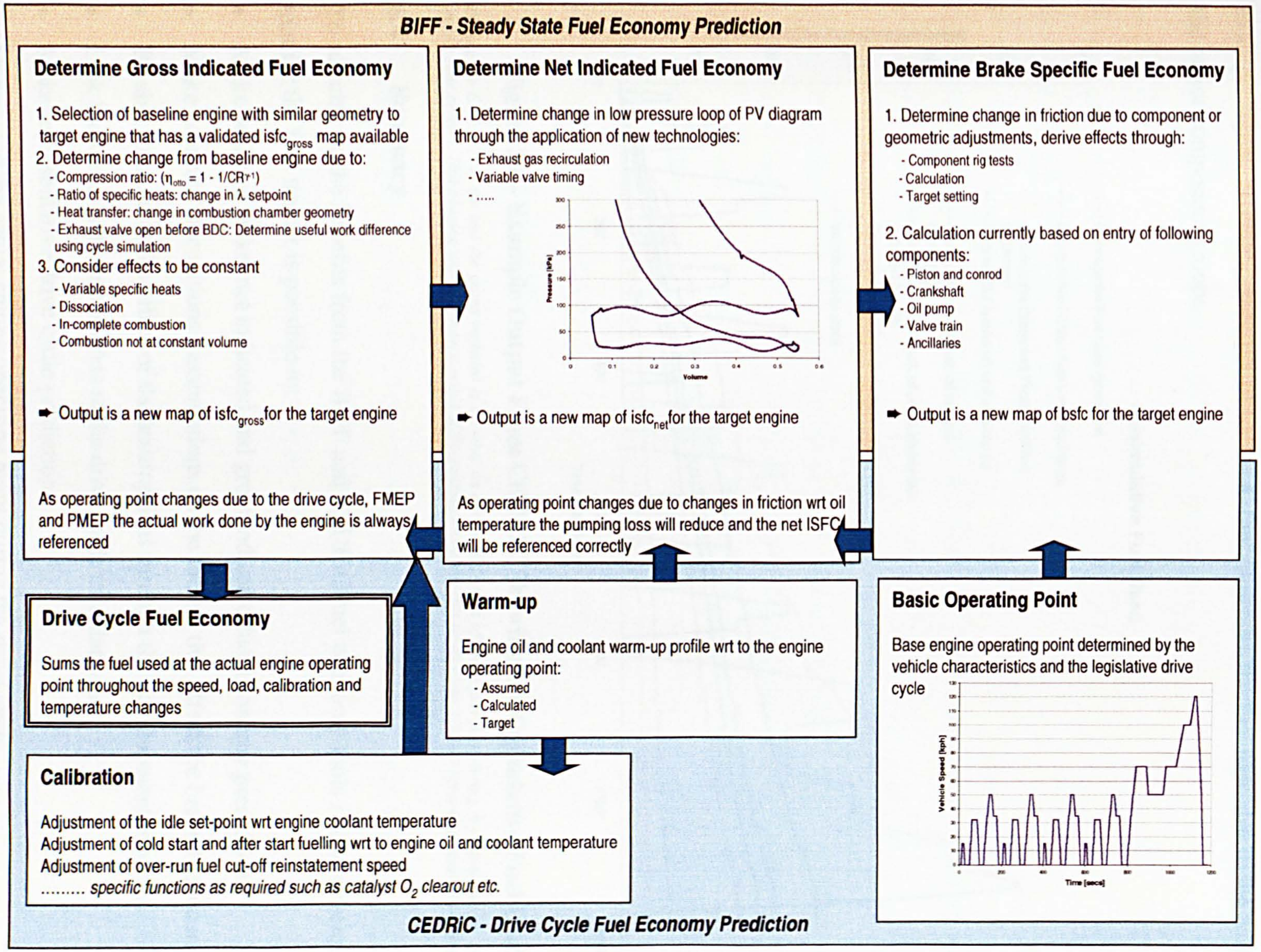


Figure 28 – Overview of Steady State and Drive Cycle Fuel Economy Calculations

Once the actual operating condition is understood it is possible to conduct a detailed analysis of the effect of individual parameters on discrete elements of the drive cycle. This enables a real insight to be gained on which areas to focus work on or elements for improvement. As an example figure 29 shows an output of CEDRiC that illustrates the fuel used due to the friction of the major component groups.

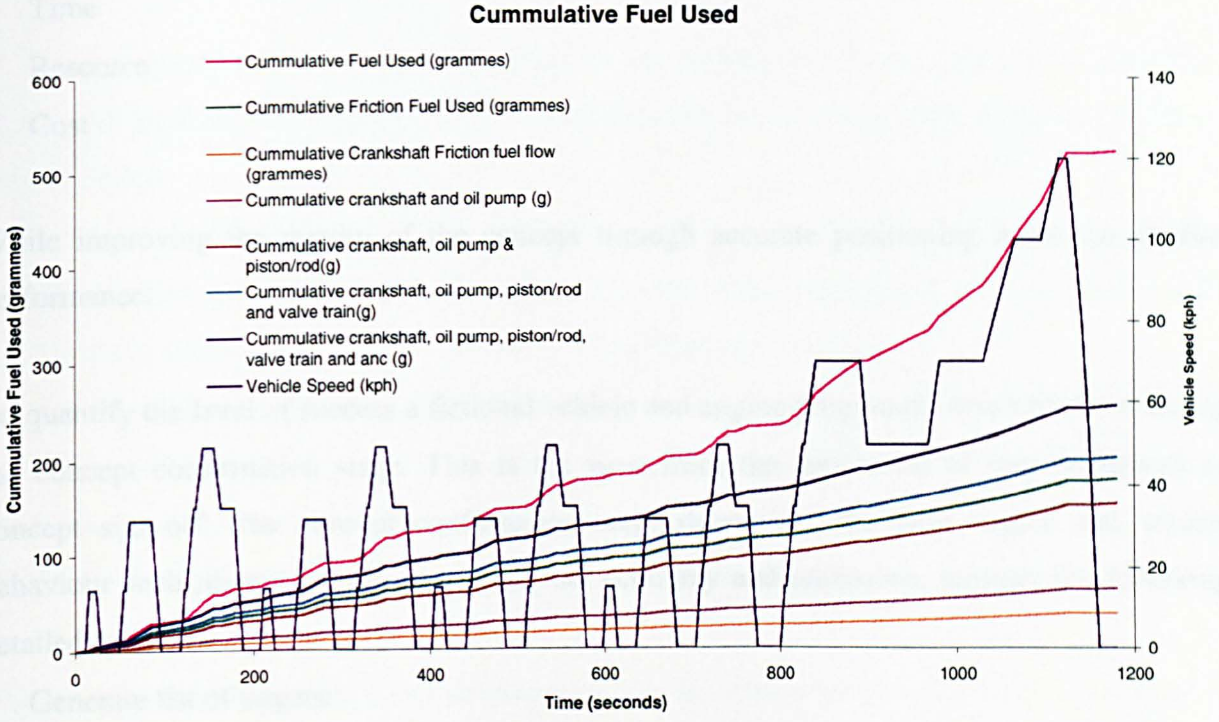


Figure 29 – Example Output From CEDRiC Showing the Cumulative Fuel Used

During the ECE part of the test the graph included is showing an unexpected trend of lower fuel flow during the accelerations than in the steady state cruises. This phasing anomaly is an artefact of the plotting process at this small scale. It is not present at larger (working) scales

6.4 Summary

To summarise the benefits from the BIFF and CEDRiC fuel economy tools I have developed are that for the first time it is possible to:

- Make accurate brake, net indicated and gross indicated fuel economy predictions
- Make accurate calculations / assumptions on the factors that affect the brake fuel economy
- Be able to monitor the effect of the assumptions through the development process
- Link the steady state predictions to the drive cycle calculations
- Make representative drive cycle predictions
- Understand the actual engine operating point during the drive cycle
- Represent calibration affects on the fuel used and the engine operating point
- Have the ability to conduct component or system level analyses on the fuel used

7 Effect Of Tools And Techniques Developed On The Development Process

The aim of this research was to provide practical tools that would be of real use during the development process and would reduce the measurables of:

- Time
- Resource
- Cost

While improving the quality of the concept through accurate positioning based on product performance.

To quantify the level of success a fictional vehicle and engine programme was examined during the concept confirmation stage. This is the time from the generation of targets through to concept sign-off. The concept confirmation stage determines the base engine and vehicle behaviour with respect to power, torque, fuel economy and emissions, through the following detailed activities:

- Generate list of targets:
- Design and procurement
- Engine Build
- Engine test bed: Baseline full load performance, power / torque
- Engine test bed: Baseline part load performance: fuel economy, emissions, combustion
- Engine test bed / rig: Baseline friction measurements
- Status: Base engine status against targets
- Engine test bed: Basic calibration
- Chassis dynamometer: Basic vehicle calibration
- Chassis dynamometer : First emissions / fuel economy tests and calibration optimisation
- Status: Vehicle emissions / economy feasibility
- Vehicle test: Performance tests
- Status: Vehicle performance
- Appraisal: Vehicle preparation
- Appraisal: Ride and drives

- Status: Concept sign-off

Two approaches were considered: a 'traditional method' using the processes available prior to this research and a 'new approach' that uses the tools and techniques described in the previous 5 sections.

In the analyses of the new method a maximum and minimum benefit condition is determined along with an arithmetic mean, but it is the mean value that is quoted. The different conditions are defined as:

- The maximum benefit is determined using the same major programme steps but removes the iterations necessary in the trial and error of the traditional approach
- The minimum benefit takes the same steps as the maximum programme but takes advantage of the removal of iteration by making more measurements to improve the quality of the knowledge of the engine which increases each of the programme steps
- The arithmetic mean is the mean value from the minimum and maximum analyses.

The duration of the concept confirmation stage can be reduced by almost 50% from 63 to 32 weeks as shown in figure 30. This can be achieved through the removal of an iteration stage that is necessary in the traditional approach after initial measurements in order to introduce changes in an attempt to meet targets at each stage of the process. Much of the extra time in the traditional method is the lead-time for new parts even when rapid prototyping methods are used. In the new approach the measurements are made to confirm the predictions and to generate correlation data that removes the need for extra stages.

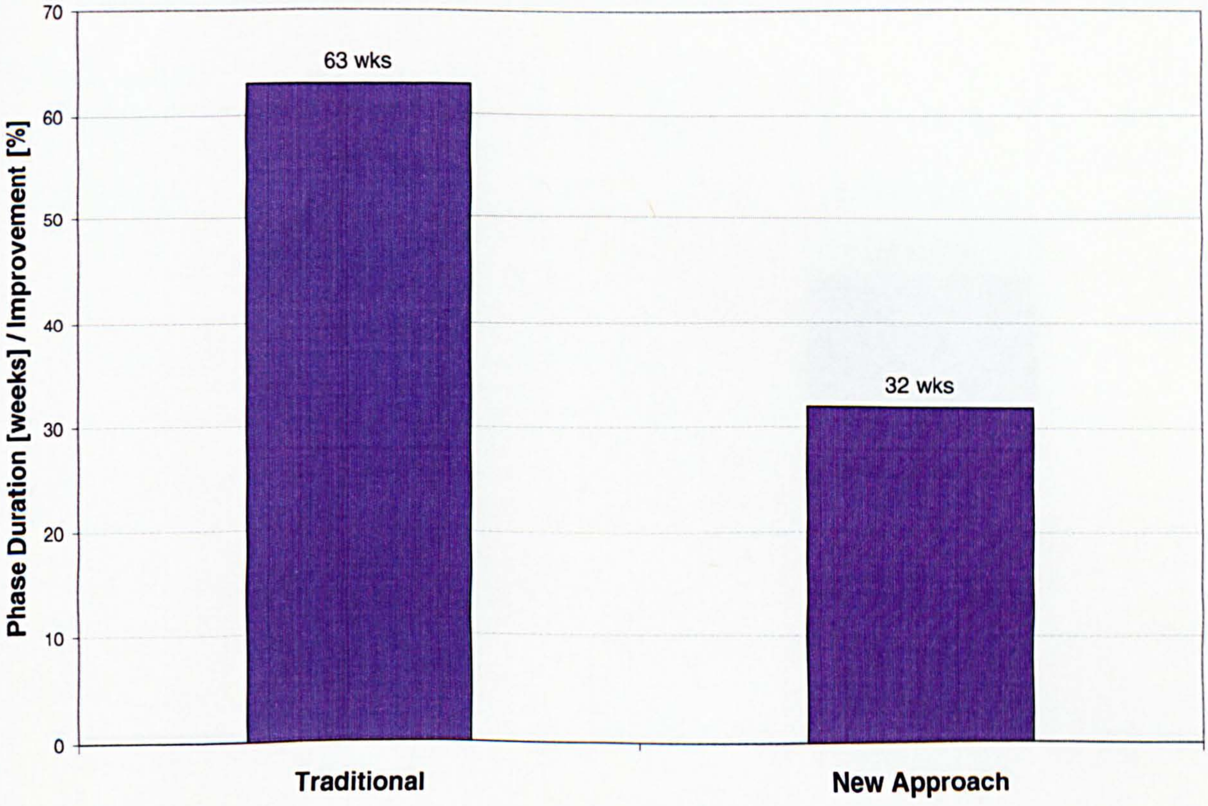


Figure 30 – Concept confirmation phase duration comparison

The resource requirements are a function of the work type and duration. With the new approach although the iterative stages are removed, more engineers are used at the start of the programme to conduct the analysis, simulation and calculation described earlier. Thus in summary, well-placed resource at the programme start has still given an overall resource reduction, as the effectiveness of the people is higher. The reductions predicted are from 12 to nearly 9 man/years, giving a reduction of nearly 30%. This is shown in figure 31.

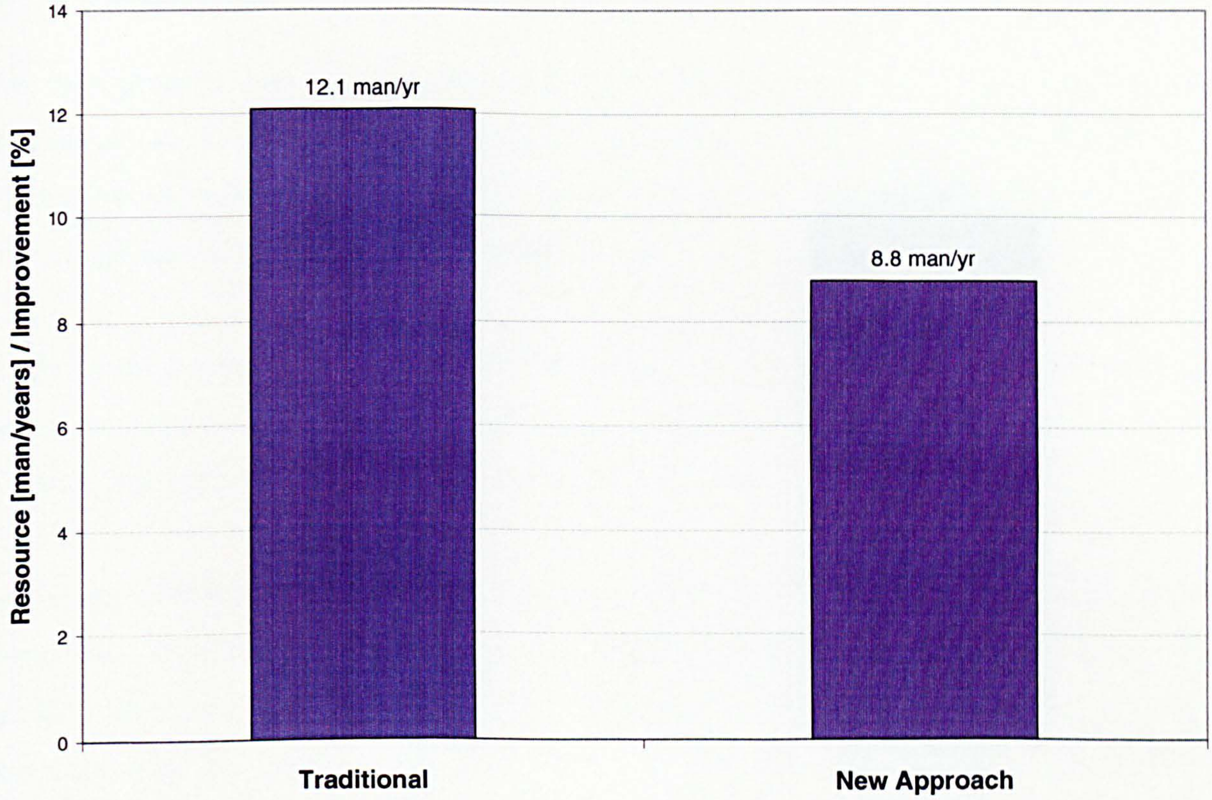


Figure 31 – Concept confirmation phase resource comparison

The cost of the concept confirmation stage is determined through the summing of the resource over time, with the resource in this context covering test facilities as well as people. As much of the improvements have been achieved through the removal of the extra iterations and the associated lead-time, the cost savings are not as impressive as those for time and resource. This is because there is an offsetting of the savings due to the extra iteration though the extra resource employed at the start of the programme. The predicted savings are in the region of 17% and are shown in figure 32.

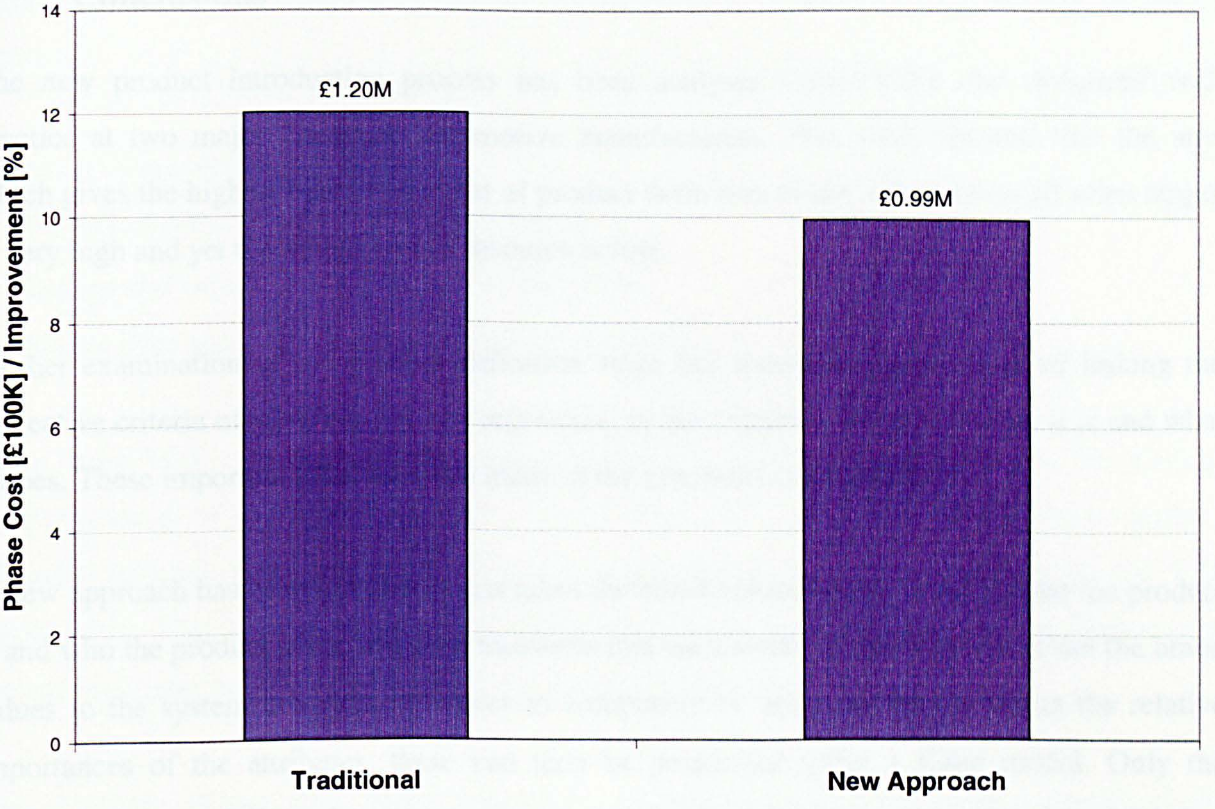


Figure 32 – Concept confirmation phase cost comparison

The final comparison made is the less tangible area of product integrity and positioning. As the comparisons made are predicted only it is impossible to be absolute in this section. However what can be stated with confidence is that using the techniques developed in the new approach it is possible to directly link the brand values to the detail of components or systems. It is also possible to predict the customer acceptance to the full load behaviour and to demonstrate this in vehicle, both of which ensure that the product is what it needs to be and can be positioned with accuracy. Also the tools developed allow auditing of detail changes on the product position and enable 'what if' studies to be conducted that will assist in the understanding of the sensitivities.

8 Conclusions

The new product introduction process has been analysed theoretically and compared with practice at two major European automotive manufacturers. This study showed that the area which gives the highest benefit was that of product definition as the influence on all other stages is very high and yet the investment in resource is low.

Further examination of the product definition stage has shown the importance of linking the subjective criteria of what it is for and represents, to the objective criteria of what it is and what it does. These important links were not made in the processes considered.

A new approach has been developed that takes the brand values which identify what the product is and who the product is for, and then translates this via a series of matrices that relate the brand values to the system or macro attributes to component or micro attributes. Using the relative importances of the attributes, these can then be positioned using a Kano model. Only the attribute of power delivery has been assigned a validated model during the research and this has enabled the required level of engine performance, vehicle weight or gearing to be determined compared with a predicted customer rating thus enabling accurate product positioning.

A vehicle has been built and programs developed to allow the demonstration of how a target vehicle/engine combination will actually feel to drive. This will allow people to drive the target product for confirmation of the package or to allow the testing of alternatives, all before any actual hardware is available, something that was previously impossible. This gives the benefits of being able to assess many alternatives, seek resolution in mutually exclusive conditions and to gain 'sign-off' of the product early in the programme allowing focus on product delivery.

The importance of fuel economy is coming to the fore with the introduction of fiscal penalties for high consumption. Techniques that I developed, validated and applied within this project have enabled the prediction of steady state and drive cycle fuel economy. These techniques are based on the fundamental relationships of engine efficiency, geometry, calibration and behaviour. Through the application of these relationships it is possible to attribute small changes in the engine to the steady state or drive cycle fuel economy and also provide a mechanism for initial component or system target setting, and subsequent monitoring through the development process.

These tools and techniques relate to:

- Further development of marque engineering
- Engine and vehicle performance demonstration
- Steady state and drive cycle fuel economy prediction

These have been compared to traditional methods to determine the benefits in the concept confirmation phase of a new programme. This investigation showed that the reductions in phase duration, resource requirements and cost could be achieved in the order of 49, 27 and 17% respectively. This is coupled with the ability to obtain a more accurate product positioning through the capacity to precisely predict the product attributes.

The objectives of this study were to develop and apply tools and techniques to assist in the product definition for the development of petrol engines. These have been achieved and demonstrated through the ability to predict product position, determine required full load performance, demonstrate full load performance and predict steady state / drive cycle fuel economy.

References

1 Product Development Performance: Strategy, Organisation and Management in the World Auto Industry
Clark, K and Fujimoto, T
Harvard Business School Press
1991

2 Competitive Advantage
Porter, M
New York Free Press
1985

3 Winning at New Products
Cooper, R
Addison Wesley
1994 2nd Edition

4 New Product Pressures
Hopkins, D and Bailey, E
Conference Board Record 8
1971

5 Resource Allocation in the New Product Introduction Process
Cooper, R and Kleinschmidt, E
Industrial Marketing Management
Elsevier Science
1988

6 Munro, S
Design for Manufacture
Munro and Associates
1994

7 Consumer Behaviour
Schiffman, L and Kanuk, L
Prentice Hall
1991

8 Consumer Behaviour, Theory and Application
Farley, J, Howard, J and Ring, L
Allyn and Bacon
1974

9 Better Design in Half The Time - Implementing QFD in America
King, R
Goal / QPC
1989

10 Kestral Report
Ali, R
Rover Group Internal Report
November 1992

11 Policy Options For The Conrol Of Car CO2 Emissions
Report Of The MVEG Ad Hoc Group No. HH/EC/VE/UK/31
Comisson Of The European Communities
September 1993

12 Fuel Economy Training Module
Robinson, A.
September 1998

13 A Comparison Of The Effects Of Downsizing Versus Component Improvements And Fuel Economy
Watson, H, Liu, Y, Kyaw, Z.H
IMECHe C389/216 - 1992